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Lodgepole Pine
the species and its management

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Lodgepole pine regeneration
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LODGEPOLE PINE
THE SPECIES AND ITS MANAGEMENT

SYMPOSIUM PROCEEDINGS

May 8-10, 1984 Spokane, Washington, USA
and repeated
May 14-16, 1984 Vancouver, British Columbia, Canada

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FOREWORD

The first "Management of Lodgepole Pine Ecosystems" Symposium was held in October, 1973 at Washington State University. Just over eleven years later, the symposium "Lodgepole Pine – The Species and Its Management" was held twice – in Spokane, Washington, USA and a week later in Vancouver, British Columbia, Canada. The symposium was repeated so that more foresters in both countries could attend. In total, over 400 people attended the symposium.

Since the first symposium in 1973, there has been a significant gain in knowledge about this fascinating species. Also, there has been an increased emphasis on lodgepole pine management in western North America. Large areas of previously unmanaged, small diameter stands now have commercial value. Lodgepole pine is also widely planted in Scandinavia and the United Kingdom.

This proceedings should be of considerable value to foresters and scientists concerned with the growing, management and utilization of this important species. Information contained in this collection of papers is broad, covering many topics. The authors did an excellent job of pulling together much of what is known about lodgepole pine. To these authors we express our sincere appreciation for a job very well done. In an effort to present a more complete coverage of several topics, individuals from Canada and the U.S.A. were asked to cooperate on papers. This worked remarkably well, as witnessed by these papers.

To the many people who contributed in some way to making the symposium and this proceedings possible.......In addition to those people listed in the earlier acknowledgements, we would also like to thank Darell Evan, Ken Hines, Lanny Quackenbush, and Russ Graham for their help with the field trip. For their special help with the proceedings, we thank Peggy Abell, Melissa Beck, and Eniss Smith and the staff at the Washington State University Office of University Publications and Printing. Also we wish to thank Mark Woods and Ken Hutchinson for their help with the cover and printing of the proceedings.

A special aspect of the symposium and this proceedings is the cooperation and sharing that has been fostered between people in the United States and Canada. Forestry in both countries can gain from the exchange of knowledge and cooperative efforts such as this.

It is our hope that this spirit of working together will increase and be strengthened in the future.

David M. Baumgartner, Pullman, Washington
Richard G. Krebill, Missoula, Montana
James T. Armott, Victoria, British Columbia
Gordon F. Weetman, Vancouver, British Columbia

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THE RESOURCE

THE DISTRIBUTION AND BOTANICAL CHARACTERISTICS OF LODGEPOLE PINE: BIOGEOGRAPHICAL AND MANAGEMENT IMPLICATIONS

Nicholas C. Wheeler
and
William B. Critchfield

ABSTRACT

Lodgepole pine (*Pinus contorta* Doug.) is the most widely distributed conifer in western North America. Its range, centered in British Columbia, spans 33° of latitude, 35° of longitude and over 3900 m of elevation. The species' edaphic and climatic tolerances are remarkable. In view of the ecological variability encountered by lodgepole pine, it is little wonder that the species exhibits considerable genetic variation.

Three well-differentiated, interfertile geographic races have evolved in the coastal, Rocky Mountain-Intermountain, and southern Cascade-Sierra Nevada regions. A fourth, endemic race of lesser significance has evolved in the Mendocino White Plains of the northern California coast. These races differ in tree longevity, dimensions, form and branchiness; needle, seed and cone characteristics; and biochemical traits.

This paper draws from a vast literature to document the variability in botanical characteristics observed in lodgepole pine. Emphasis is on the subspecies *latifolia*. Observed patterns of variation are discussed in conjunction with day-to-day management decisions and current views on the biogeography of lodgepole pine.

INTRODUCTION

Within the last 20 years, lodgepole pine has achieved significant stature as a commercial forest species, not only in North America but throughout much of northern Europe. Also, because of the species' commercial importance, large natural range, broad ecologic amplitude, and predominantly serotinous cone habit which simplifies seed collection, lodgepole pine has been well studied. In fact, it is probably as well characterized, botanically, as any forest tree species in the world.

A number of papers have thoroughly reviewed the literature on the distribution and botanical characteristics of lodgepole pine (Critchfield, 1957, 1980 a, b; Edwards, 1954, 1955). Consequently, we have attempted to deal with this fundamental requirement as succinctly as possible, drawing significantly from previous reviews (Critchfield, 1980 a, b). In so doing, literature citations have been largely dismissed. Interested readers may refer to the earlier review papers for comprehensive citations. The remainder of this paper focuses on the interpretation of observed patterns of variability in natural stands and provenance tests and how this knowledge helps answer the following questions: i) How did the lodgepole pine attain its present distribution and ii) how can we, as managers, better manipulate our forest resource.

DISTRIBUTION AND HABITAT

Lodgepole pine is the most widely distributed conifer in western North America. Its range, centered in British Columbia, spans 33° of latitude, 35° of longitude and over 3900 m of elevation (fig. 1). While other species may have larger ranges, none match the remarkable edaphic and climatic tolerances of lodgepole pine. It is the principal tree species on over 26 million hectares of forest land in western Canada and the United States.

The natural range of lodgepole pine can be subdivided into three principal regions: (1) the Pacific coast from Yakutat Bay, Alaska, to northern California including the entire region west of the Coast Mountains of Alaska and British Columbia, the northern Cascade Range, and the Klamath Mountains and north coast ranges of California; (2) the mountain chain comprising the Cascade Range, Sierra Nevada, and the high mountains of southern California and northern Baja California; and (3) the Intermountain region and Rocky Mountain system from central Yukon to eastern Oregon and southern Colorado, with eastern outliers from the Caribou Mountains of northern Alberta to the Black Hills of South Dakota.

Coinciding with these major geographic subdivisions are conspicuous patterns of variation in numerous morphological, physiological and biochemical traits. The species is now generally recognized as being comprised of three broadly distributed subspecies with the following geographic affiliations:

1. *P. contorta* ssp. *contorta:* Pacific Coast
2. *P. contorta* ssp. *murrayana:* southern Cascades, Sierra Nevada and the mountains of southern Baja California.
3. *P. contorta* ssp. *latifolia:* Rocky Mountain and Intermountain regions, northern Cascades, Washington.

A fourth, endemic, taxa (*P. contorta* ssp. *bolanderi*) occurs in the Mendocino White Plains along the northern California coast. The taxonomic status of this population is still questionable. To be sure it represents an excellent example of an edaphic ecotype.

In the coastal region, subspecies *contorta* is sometimes called shore pine. Here, the species occupies a variety of extreme

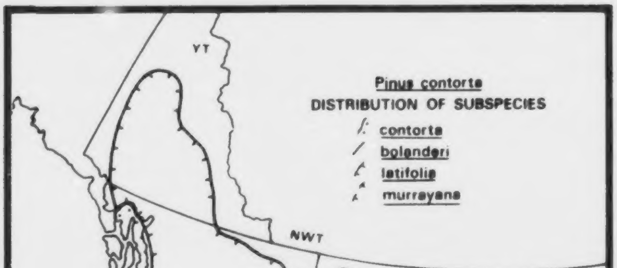


Figure 1.–Natural distribution of the subspecies of lodgepole pine. The southernmost extension of ssp. *murrayana* is omitted in Baja, California.

habitats that are all unfavorable for the growth of possible competitors. In the far north, bogs and muskeg are its principal habitat, and a slowgrowing muskeg ecotype extending south to Washington may have evolved on these sites. In the central and southern parts of its coastal distribution, the species also grows on cliffs, sand dunes, and rocky sites. Inland from the immediate coast, it occurs as high as 1525 m on southern Vancouver Island (Garman, 1973), on serpentine soils in the San Juan Islands and on excessively drained, nutrient-poor glacial drift in the Puget Sound region. In western Washington there is some evidence that edaphic ecotypes have evolved on serpentine sites. The species also occurs on serpentine and other ultramafic soils in the low coastal mountains of northwestern California. Near the southern coastal limits a dwarf form grows on the Mendocino White Plains, a few kilometers inland from the coast. This unique pygmy forest has "one of the most acid soils known anywhere," an extremely infertile podzol with a cemented hardpan and a pH of 2.8-3.9 (Jenny *et al.*, 1969). This population can be considered an edaphic ecotype: seedlings of White Plains origin survived and grew much better on a White Plains site than seedlings of other origins, including the nearby coastal bluffs. It is treated here as a subspecies (*bolanderi*).

Outside the coastal region, lodgepole pine is much more generally distributed. In the Cascade Mountains of Washington and Oregon it is an important seral species in several forest zones, primarily on the drier eastern slopes. It has a more permanent status on marginal sites, including serpentine soils in the Wenatchee Mountains, and both droughty, sandy soils and poorly drained, highly organic soils in the northwest Oregon Cascades. In south-central Oregon, lodgepole pine forms extensive climax forests on pumice deposited by Mt. Mazama 6600 years ago. Its ecological status is poorly understood in the mountains of California (Rundel *et al.*, 1977) but it is the most common tree on sites with shallow water tables, such as meadows and stream benches. It also dominates the poorly-defined lodgepole zone, where it may form extensive pure stands in glacially scoured basins, as in the high country of Yosemite National Park. It is a minor component of the Sierra Nevada subalpine forest, and near the timberline it sometimes grows as a shrub about 2 m high.

Most of the commercial range of lodgepole pine is in the Intermountain and Rocky Mountain regions, and its wide distribution in this part of its range is attributed primarily to forest fires. Serotinous cones are present in many stands, and they contain a large seed reserve released by fire. Other attributes that make the species an aggressive pioneer in these regions are the regular and abundant production of seeds from an early age, the small size and high dispersal ability of the seeds, and relatively rapid juvenile growth.

Rocky Mountain lodgepole pine is also notable for its intolerance, and is considered a seral species throughout this region, from the Yukon to Colorado and eastern Oregon. Virtually all of the extensive lodgepole forests in Alberta are believed to be successional and of fire origin. In a few Rocky Mountain plant communities lodgepole pine is considered a climax species, but most of the extensive–and apparently permanent–lodgepole stands of this region are interpreted as prolonged seral stages (Pfister and Daubenmire, 1975). A different interpretation is that Rocky Mountain lodgepole pine has evolved a set of characteristics that make it (1) periodically fire-prone, and (2) able to perpetuate itself after fire, a combination that enables it to maintain dominance on many sites (Brown, 1975).

BOTANICAL CHARACTERISTICS

Coastal Lodgepole Pine (ssp. *contorta*)

These thick-barked, frequently twisted trees are relatively small and inherently branchy (fig. 2). The leaves are short, rather narrow, and have more stomata per unit area than the leaves of inland races. Flowering is abundant, and tends to be protogynous. Cones are relatively small and light with thin

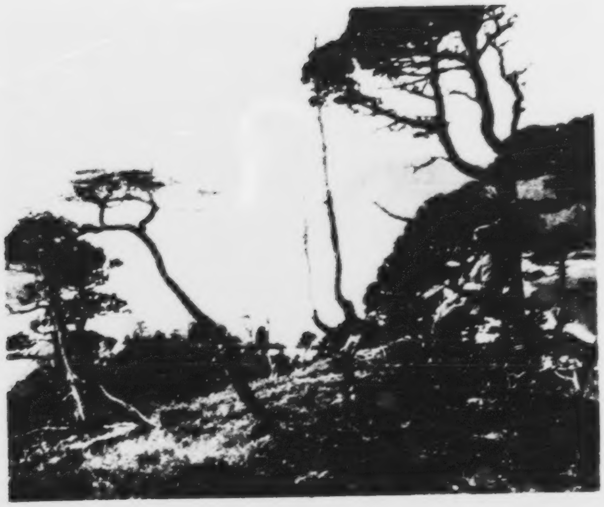


Figure 2.–Lodgepole pine thrives on Kogish spagnum peat soils throughout the north coastal range of ssp. *contorta.* Twisted stems and bushy crowns give the appearance of bonsai to these trees which may live for over three hundred years.

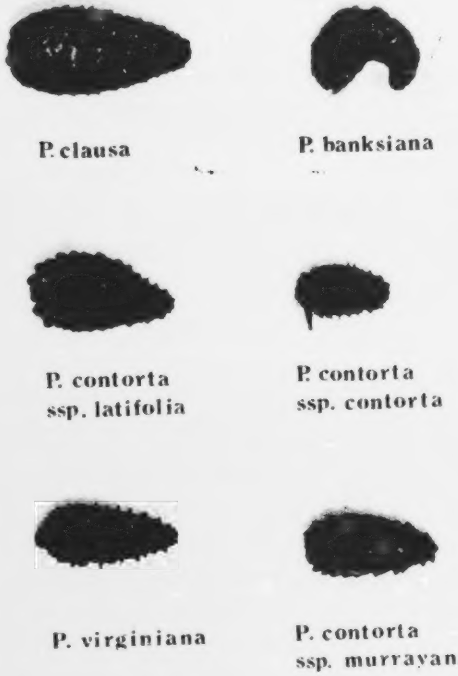
scales and long, narrow spines. Apophyses are only moderately enlarged. Cones are typically sessile, non-serotinous, strongly reflexed and asymmetrical although serotiny is increasingly common in valley systems that dissect coastal mountain ranges. In these river valleys gene flow with interior populations is assumed to occur. The seeds are small to medium-sized and lack seed coat mottling. Germination is slower than that of the interior races. Early height growth is nearly always faster than that of inland origins at the same latitudes.

Sierra-Cascade Lodgepole Pine (ssp. *murrayana*)

The most distinctive race of lodgepole pine, it is inherently slow-growing in height. Diameter growth is more sustained, and the thin-barked trees reach much greater diameters (and probably greater ages) than elsewhere in the species range. This race appears to have a stable ecological role and a distribution that is not related to fire. The relatively short leaves are the widest in the species. The seeds are by far the largest, often with light-colored seed coats and wings, and the seedlings have more cotyledons than those of other races. The cones are long but relatively light-weight with flattened apophyses and triangular, reflexed spines. The subspecies is unique in having nearly symmetrical, sub-pedicilate cones (fig. 3). They are non-serotinous and project perpendicular or slightly reflexed to the stem.

Rocky Mountain-Intermountain Lodgepole Pine (ssp. *latifolia*)

The extensive range of this race includes most of the commercial stands of lodgepole pine. The trees are tall but do not reach large diameters, the bark is usually thin, and the leaves are long and moderately wide. Cones are produced regularly from an early age. The cones are most often serotinous, opening at high temperatures, and the aggressive behavior of this race after fires has led to its dominance over extensive area (fig. 4), often in tremendously overstocked stands. The trees are intolerant, and the group is considered successional in most forest communities. The cones are hard and heavy, with protruberant apophyses. They may be reflexed, projecting, or semi-erect on the branch. Semi-erect cones, present only in this race of lodgepole pine and in jack pine, are most common in regions removed from the present zones of natural hybridization with jack pine. Cones are sessile and typically very asymmetric. Tremendous variability in cone size and shape occurs both within and between populations (fig. 5). The seeds are small and highly dispersable, retain their viability for many years in serotinous cones and germinate rapidly without pretreatment. They are frequently mottled. The seedlings have few cotyledons and suffer heavy mortality from drought and frost-heaving. Juvenile growth is relatively rapid. Local variations include (1) a high frequency of three-needled fascicles in the Yukon and northern Alberta, or (2) in stands in southern interior British Columbia and adjacent United States, the variable occurrence of thick bark, repeated stem forking, unusually fast juvenile growth, a low incidence of serotinous cones and a high incidence of semi-erect cones.



P. clausa

P. banksiana

P. contorta
ssp. latifolia

P. contorta
ssp. contorta

P. virginiana

P. contorta
ssp. murrayana

Figure 3.–Representative cones of lodgepole pine subspecies and other taxa in the genus *Pinus,* subsection *Contortae.*

Figure 4.—Subspecies *latifolia* is recognized as an aggressive pioneer. In the Canadian Rockies, lodgepole pine rapidly establishes burned sites resulting in expansive, even-aged stands that may reach from valley floor to treeline.

Mendocino White Plains Lodgepole Pine (ssp. *bolanderi*)

Restricted to a small area of highly acid podsol soil near the coast of Mendocino County, California, this race is probably an edaphic ecotype derived from the contiguous coastal race (fig. 6). Flowering is protogynous. The trees are extremely heavy pollen producers, and compared to coastal trees they produce high ratios of male to female strobili. The leaves are short, narrow, and lack resin canals. The cones are reflexed, heavy, knobby, and often serotinous.

BOTANICAL CHARACTERISTICS OF INTEREST TO THE MANAGER

Characteristics expressed throughout the ontogeny (life cycle) of an individual tree or stand may potentially impact our decisions on how to manage these stands. This is certainly true for lodgepole pine. We have chosen to briefly discuss a series of traits that are expressed at i) time of reproduction, ii) time of seedling establishment and iii) time of stand establishment and growth. Some of these traits have been well studied and are already considered in management prescriptions. Others are less-well characterized and are noted here in hopes that their mention may stimulate research or investigation that will lead to a better understanding of this organism.

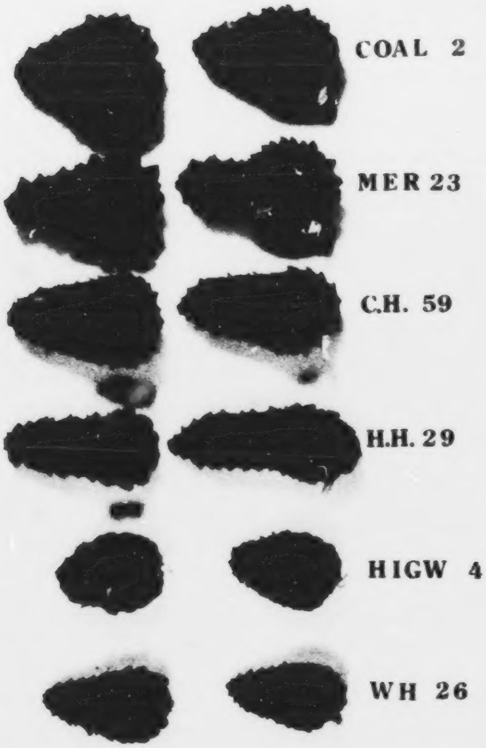


Figure 5.—Top (left) and side (right) views of *P. contorta* ssp. *latifolia* cones demonstrating typical variability observed in size, shape and scale characteristics. Identifiers designate specific trees and populations from which cones were collected (Wheeler, 1981).

Figure 6.—Mature, reproducing stand of *P. contorta* ssp. *bolanderi*. Trees are growing on a highly acidic, podzolized soil.

In the main, characteristics discussed in this section are mentioned in the context of improving individual tree and stand productivity. Essentially all of the traits have been shown to be highly variable, either in lodgepole pine or some other tree species, and in many instances the traits have been shown to be heritable. These two points are critical to our discussion, for without variability there is no opportunity to exercise selection for the phenotype of choice, and without a genetic basis there is no opportunity to transmit the selected trait to the next generation. To capture the potential gain associated with these traits, tree breeding and selection programs are necessary. To date tree breeders have confined their efforts to improving relatively few traits such as height, diameter, disease resistance, etc. Many of the traits mentioned here constitute "components" of growth. Breeding for components of growth is expected to become increasingly important in forest trees (Cannell and Last, 1976). By collectively being more aware of the types of things that can contribute to increased forest productivity, hopefully we can progress toward an improved lodgepole pine at a rapid pace.

Serotiny

An ensemble of traits contribute to lodgepole pine's role as an aggressive pioneer species within the range of subspecies *latifolia* (Lotan, 1976) but cone serotiny remains the single most significant factor. As managers, we are interested in the regeneration not only of naturally disturbed sites but of harvested sites as well. Because serotiny (and the conditions contributing to its predominance) plays such a key ecological and silvicultural role in the establishment and maintenance of vast areas of interior western forests, it is imperative we have intimate knowledge of individual stand and region cone characteristics (Lotan, 1975, 1976). This knowledge can aid considerably in developing silvicultural and fire management prescriptions for stand reestablishment.

It is unclear whether serotiny is an ancestral or derived condition but it now seems certain that it is largely an evolutionary response to frequent destructive fires (Linhart, 1978; Perry and Lotan, 1979; Givnish, 1981; Muir and Lotan, 1984). Not all lodgepole pine subspecies sport serotinous cones. The trait is absent in ssp. *murrayana* and infrequent along the coast (ssp. *contorta*) except for stands susceptible to gene flow from interior populations (Critchfield, 1980 b). In neither case is lodgepole pine considered a fire-related pioneer. In the Rocky Mountain-Intermountain region, where fire is a common feature, the frequency of closed-cone trees is highly variable. Muir and Lotan (1984) were able to attribute a considerable proportion of the between-stand variation in serotiny to the nature of the stand-initiating disturbance; fire initiated stands contained more closed-cone trees. A detailed study with pitch pine (*P. rigida*) demonstrated similar results (Givnish, 1981). For many of you this relationship seems like a foregone conclusion. However, the persistence of open-cone trees, often in high frequency, throughout the range of ssp. *latifolia,* has clouded our interpretation of the exact role of fire in maintaining this trait. Given the patterns of serotiny observed in natural stands it appears that the predominant cone type will shift through time in response to the disturbance regime (Perry and Lotan, 1979; Muir and Lotan, 1984). In other words, neither condition is selectively advantageous all the time for if it were, the polymorphism would not likely be maintained (Hartl, 1979).

Therefore, it is important for the forester to recognize the population structure (with respect to serotiny) of the stands he is managing as well as being aware of the current ecological and silvicultural characteristics of that stand. This information may then be integrated into the management plan on a site by site basis (Lotan, 1975, 1976). More complete treatments of the physical cause of serotiny, its genetic basis and the observed distribution patterns, may be found in Lotan (1976) and Critchfield (1980 b).

Seed Quality

Naturally, as harvesting of lodgepole pine has increased so has artificial regeneration. The number of lodgepole pine trees now being planted annually, worldwide, may well be over 100 million, with much of the planting in northern Europe. Consequently, handling of seed, particularly in a nursery environment, is an important step in successful reforestation. A number of botanical characteristics associated with seed and seedlings are of real interest to reforestation efforts. These become increasingly more important as seed from expensive tree improvement programs become more available. We will discuss seed germination and how it may influence nursery strategies. First, some general observations.

Lodgepole pine seed has no absolute stratification requirement for germination, but seed stratified for as little as 2 weeks germinates faster than untreated seed (Critchfield, 1957; Roche, 1962). Stratification is recommended for 4 weeks in Britain (Forestry Commission, 1976), and 3 to 4 weeks in Alberta (Wang, 1979) to insure maximum germination performance from all sources. Seed stored in serotinous cones retains its viability for many years (Bates, 1930; Trappe and Harris, 1958; Wang, 1978, 1979). Western Alberta seed from cones of all ages was more than 90 percent germinable (Ackerman, 1966). Clements (1910) obtained 8 percent germination in seed from cones that persisted on a tree for 75 years. Wang (1979) notes that germination vigor and early seedling growth is highly correlated with seed weight.

Of particular interest to nursery managers is germinative capacity and speed. Large between and within provenance differences have been observed for both traits (Critchfield, 1957, 1980 a; Illingworth, 1976; Hagner, 1980). While there appear to be some general trends associated with latitude and elevation for both traits, tree-to-tree variation is probably of greatest concern to the manager. Late germinating seed are at a severe disadvantage in the nursery bed. It is easy to see how this trait alone can contribute considerably to the proportion of trees culled in the nursery.

There are a number of reasons why unplanned selection for germinative speed may be undesirable, but one that most concerns tree breeders is that the genetic structure of the outplanted crop may be significantly influenced. Weyerhaeuser's tree improvement program illustrates this point. Weyerhaeuser has invested handsomely in selecting parent trees, testing their progeny and developing seed orchards to produce seed of high genetic quality (with respect to growth). In the south, we collect seed by individual clone and raise it in the nursery in individual lots. While there is considerable variation in germination speed among clones the chance that a good performing clone will be suppressed is eliminated. In the West we still bulk our improved orchard seed by seed zone (origin of parent tree) rather than collecting by clone. I (N.W.) suspect we are losing some of the genetic gain potential from our orchards because seed of good performers is being suppressed as a result of germinating late. The loss is manifest in differential culling of genotypes, in this case based upon selection for a trait that is irrelevant to our interests in yield.

As tree improvement programs for lodgepole pine mature and begin producing seed, program managers are encouraged to keep this trait in mind. The relationship between seed weight and germinative vigor should also be investigated further, on a tree to tree basis.

Root Characteristics of Young Trees

A number of physiological and morphological traits associated with seedlings play important roles in the establishment and early growth of plantations. As we plant more trees, especially trees of known genetic worth, these traits will take on added significance. They may, in fact, be contributing appreciably to the genetic value associated with the better seed sources. A couple of traits of common concern for early plantation success are drought resistance and frost tolerance. Research with lodgepole pine has demonstrated that considerable within-species variability exists for both these traits (Dykstra, 1974; Jonsson, *et al.*, 1981). This variability provides an opportunity for reducing mortality and growth loss due to frost and drought through judicious selection of seed sources. The best seed sources may not be the local ones.

Another array of traits worthy of note are those associated with nutrient uptake efficiency. A strong case can be made for the importance of uptake efficiency to potential growth rate. A soon-to-be published assemblage of papers discusses the opportunities that exist for improving plantation productivity through exploitation of variation in such traits (Bowen and Nambiar, 1984). Specific traits associated with nutrient uptake include i) root growth potential (RGP), ii) mycorrhizal associations and iii) root morphology.

Burdett (1979) has shown that seedling survival following outplanting is closely tied to root regeneration in lodgepole pine and work with radiata pine has demonstrated root growth potential is a highly heritable and variable trait (Nambiar, *et al.*, 1982). Trees with the ability to regenerate roots rapidly after transplanting have an obvious advantage for both survival and growth and are preferred for plantation establishment. Ritchie and Dunlap (1980), in a comprehensive review on the subject note that root growth potential is a key indicator of planting stock quality and is affected by nursery practices and cold storage regimes. Apparently, RGP is dependent on the status of dormancy. Ritchie and Dunlap (1980) note that one of the important unknowns regarding RGP is "The nature of the chilling requirement (temperature, duration) for various species, provenances and important families." As we enter the period in which genetic control of planting stock is commonplace, assessment of RGP on a family basis should be seriously considered. This will likely lead to individual family prescriptions for nursery and storage handling.

Lodgepole pine possesses relatively few fine roots or root hairs (Mexal, *et al.*, 1979) and apparently relies heavily on mycorrhizal association for nutrient uptake. Clearly, the ability to form symbiotic associations with various ectomycorrhizal fungi is advantageous under such conditions. Cline and Reid (1982) inoculated ten provenances of lodgepole pine with three species of ectomycorrhizal fungi and observed large provenance differences in ability to form mycorrhizae with the different fungi. Specific associations between host and mycorrhizal fungi strains or species have been reported for other species as well (Marx and Bryan, 1971; Theodorou and Bowen, 1970; Long, 1973; Mason and Pelham, 1975). The inference is clear. Selection of the proper source can eliminate a lot of grief when it comes to assessing plantation success.

Finally, root morphology and/or configuration can play an important role in determining a plant's nutrient uptake capacity (Nambiar, 1983; Bowen and Nambiar, 1984). For instance, the production of fine roots (more roots per unit root weight) is a highly heritable trait in loblolly and radiata pines (Long, 1973; Nambiar, 1983). By investing in increased fine root structure rather than in few, large roots, plants have greater access to available soil resources, especially those poorly mobile elements such as phosphorus (Nambiar, 1983). Although Mexal *et al.* (1979) noted a lack of roothairs in lodgepole pine, an investigation of a broader genetic spectrum would almost certainly reveal a range of root morphologies among which selection could be made.

A better understanding of these types of traits may be necessary before we can achieve major improvements in plantation productivity.

Crown Characteristics

Finally, we draw attention to an array of traits associated with mature trees – those traits that combine to produce the living and non-living crown. Most foresters and lumbermen are familiar with characteristics such as branch retention and size or tightness of knots. These are traits that directly influence the economic value of that stick of wood. However, other crown traits that are no doubt of considerable economic value are given little attention, at least in the United States. Number of branches per whorl, branch length, and extent of branch subdivision fit in this category. Any trait that directly or indirectly affects the photosynthetic surface of the crown will ultimately impact stem and stand productivity. As a prime example we can consider the Finnish concept of the ideal forest tree ideotype (Karki, 1983). This tree is one which possesses very short, finely subdivided branches of small diameter. The tree crown consumes very little space, making it ideal for plantation management under high density conditions (Karki, 1983). Furthermore, this phenotype results in a high harvest index (a high ratio of stem wood to total tree biomass). The Finns have actively sought parent trees of this nature for their Norway spruce and Scots pine improvement programs. Similar crown phenotypes occur in lodgepole pine (fig. 7). The prospects of increasing wood production per unit of land by using such an ideotype seems encouraging.

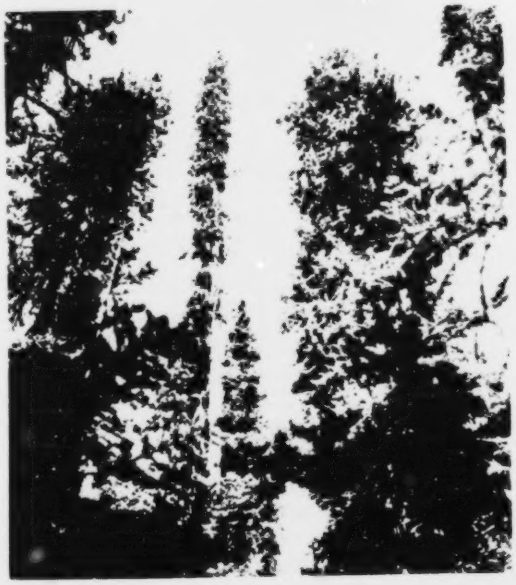


Figure 7.–Narrow-crowned individuals such as this one could be used to improve stand productivity by increasing planting-stock density.

BIOGEOGRAPHY

When discussing the widespread distribution of lodgepole pine, it is appropriate to consider questions pertaining to the natural history of the species. The answers are largely of evolutionary interest but may also be of considerable practical value. Knowledge of species history confers knowledge of population structure which in turn can be used to develop tree improvement strategies for breeding and seed source movement. In this section we briefly discuss current views on the biogeography of lodgepole pine. It should be noted that two fundamentally different approaches exist for reconstructing species history: inferences from the distribution and variation of living organisms, and inferences from the fossil record (Critchfield, 1984). Evidence obtained from both approaches is used here to develop a general perspective; we then rely on variation in botanical traits to refine our view of species biogeography.

While lodgepole pine has probably been a constituent of the conifer forests of western North America for several millions of years, poleobotanical evidence suggests it was relatively uncommon until the late Pleistocene (reviewed in Critchfield, 1980 a, b, 1984). By that time it was widespread south of the Wisconsin ice sheet in the western United States and appears to have played a major role in early post-glacial revegetation of disturbed lands (reviewed by Wheeler, 1981). South of the limits of the continental ice sheets, the principal races of lodgepole pine appear to have been influenced relatively little by repeated glaciation. As noted, these races are geographically isolated from each other in the south, and their distinctness as characterized in our section on botanical traits suggests they have been genetically isolated for many millenia (Critchfield, 1984). In contrast, *most or all* northern populations in the subspecies *latifolia* and *contorta* achieved their present distribution in the past 10 to 14 thousand years. Considering the short period of time available for such a vast recolonization effort, several questions may be asked. We address two. First, what traits does lodgepole pine possess that contribute to its ability to rapidly recolonize disturbed lands? Secondly, did lodgepole pine persist in multiple glacial refugia thus aiding the recolonization effort?

In many respects lodgepole pine may be characterized as a Pleistocene opportunist (Critchfield, 1984) in that it has only recently (geologically speaking) achieved major forest species status. This probably is attributed to the species' ability for explosive population growth and rapid migration abilities. The traits that allowed lodgepole pine to be so successful as a colonizer of deglaciated sites are essentially those that confer pioneering status to the species today. This suite of traits make lodgepole pine unique among the western conifers with respect to natural reforestation of disturbed habitats. A brief list of these traits includes the following:

Precocity–Lodgepole pine is reproductively active at a very early age.

Serotiny–This trait contributes to the species colonizing ability in many ways. Young trees (less than 30 years of age) are generally non-serotinous, thus allowing for an annual seed fall. Coupled with precocity, this would allow young migrants to contribute propagules for continued advancement at a relatively rapid rate. With the onset of serotiny in older stands, immense seed reserves are developed. A fire in such a stand may release millions of seeds per hectare. This is the principal factor associated with the species' ability for explosive growth and a trait that confers considerable advantage to lodgepole pine relative to other conifers when it comes to successful site capture.

Seed Size–Lodgepole shares, with jack pine, the distinction of having the smallest seeds in the genus *Pinus*. These lightweight seeds have a slow rate of fall, thus allowing for wind dispersal of up to several miles (Bannister, 1965). Wind-blown seed have also been observed scudding across crusted snow (Lotan, 1976). The significant point here is that sexual propagules of lodgepole pine may be dispersed over considerable distances which would surely benefit rapid migration.

Germination–Lodgepole pine seed has only minimal germination requirements and seedlings may establish themselves under relatively adverse climatic and edaphic conditions.

Frost-hardiness–Young lodgepole pine seedlings, in general, are relatively frost-hardy.

Growth Rate–Lodgepole pine possesses rapid juvenile growth that aids in establishment of new sites.

Edaphic Requirements–One of lodgepole pine's most distinguishing characteristics is its ability to thrive on a broad spectrum of soil types from waterlogged organics to well-drained glacial outwashes and nearly everything in between.

Considering these many reproductive and growth-related traits that contribute to lodgepole pine's ability to colonize disturbed habitats, one can envision the species virtually pursuing the retreating glacial front. In fact, this is the general picture as told by the paleobotanists. Lodgepole pine must have survived Pleistocene glaciation south of the ice and migrated north to its current range following glacial retreat. However, consideration of patterns of variation in a number of botanical traits including simply inherited biochemical markers (isozymes) suggests there may be more to the story than this (Wheeler and Guries, 1982 a). In addition to the major refugium located south of the Cordilleran ice, possible refugial sites in west-central Alberta, the Yukon Territory and coastal British Columbia and Alaska have been suggested (Hulten, 1937; Hansen, 1947; Heusser, 1960; Terasmae, 1973; Critchfield, 1980 b; Wheeler and Guries, 1982 a). Conclusive fossil evidence for the existence of most of these sites remains lacking (for an exception, see Warner *et al.,* 1982) although geological support can be generated for all three (Hulten, 1937; Dahl, 1946; Coulter *et al.,* 1965; Hughes, *et al.,* 1968; Derksen, 1976; Hopkins, 1972).

A review of the literature addressing botanical variation in natural populations of lodgepole pine provides the following evidence for the persistence of the species in refugia other than those south of the ice.

Isozymes–Wheeler and Guries (1982 a) conducted a range-wide survey of allelic variation in 42 loci, coding for soluble proteins in lodgepole pine. The gene frequency data obtained were used to estimate standard genetic distances (a measure of genetic similarity) between pairs of populations (Nei, 1972). When these data were fed into a cluster analysis it was found that Yukon and northern British Columbia populations were relatively distinct from the ssp. *latifolia* populations to the south (fig. 8).

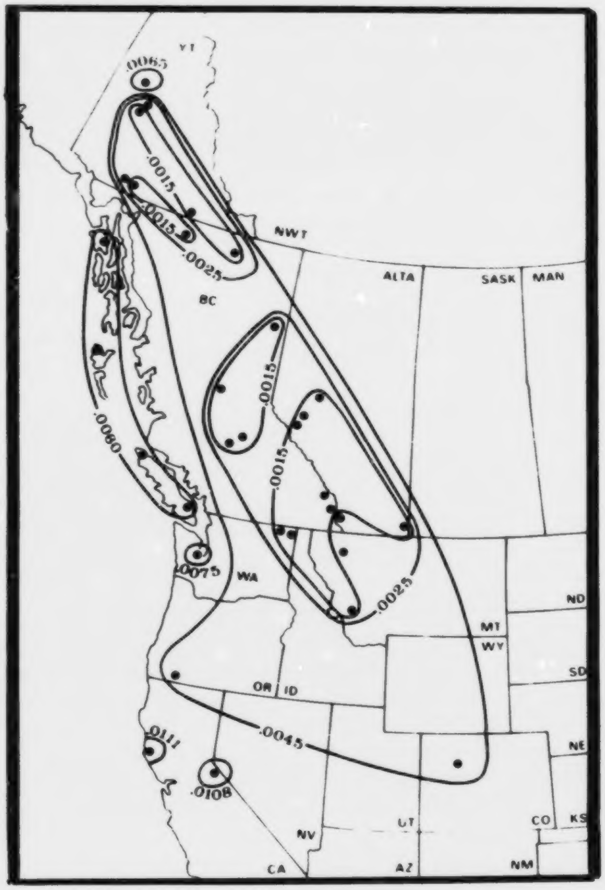


Figure 8.–Population clustering based on Nei's genetic distance measure.

The magnitude of the difference between the two groups was about as great as that between southern B.C. populations and a southern Oregon population which technically belongs to spp. *murrayana*. This pattern is consistent with the theory that northern populations isolated in glacial refugia diverged genetically to an extent commensurate with the period of time they were separated from the main body of the species. Further support for genetic divergence of northern populations comes from a survey of rare alleles, a number of which occur either only in the north or only in the south (Yeh and Layton, 1979;

Wheeler and Guries, 1982 a). The mere presence of a large number of rare alleles in the north is inconsistent with biogeographical hypotheses developed for rapidly migrating populations.

A similar case can be submitted for the northern populations of ssp. *contorta*. Coastal populations in British Columbia and Alaska are electrophoretically quite distinct from one another and from one southern coastal source near Shelton, Washington (Wheeler and Guries, 1982a). Such divergence would not be expected if all north coastal populations derived from a single parental population south of the ice. Also, rare alleles were frequent in coastal populations, a sign of historical stability of these populations (Wheeler and Guries, 1982 a). Other electrophoretic traits such as levels of population heterozygosity, lend support to the theory that North Coastal populations are not recent migrants from the south.

Provenance Tests – A study of cortex resin monoterpenes from trees growing in British provenance tests led Forrest (1980, 1981) to group North Coastal populations separate from coastal populations south of Vancouver Island with the exception of a single outlier in western Washington. This split coincides with growth and crown form results obtained by Shelbourne and Miller (1976) who proposed that North Coastal populations be considered an edaphic ecotype distinct from coastal populations to the south. The uniform expression of metrical and biochemical traits within the region and the distinction noted between regions again leads one to believe they (north and south populations) were not recently derived from the same genetic base. This raises an interesting point, however. In the case of electrophoretic evidence, the north coastal populations were quite distinct from one another; here, they are similar. How can the same conclusion regarding origin be drawn from such different patterns of variability? Stated simply, most of the traits that are uniform within the region are probably under relatively strong selective pressures while the others are not. Growth form, edaphic preference, etc., are traits that, under the circumstances encountered by ssp. *contorta*, are of considerable adaptive value. It is possible that those traits conferring adaptedness to lodgepole populations were retained in one or more separate refugia in the north throughout the full glacial. This seems plausible considering the relative uniformity of climatic and edaphic conditions experienced in this region today.

Isozymes, on the other hand, have seldom been demonstrated to possess strong adaptive significance; they appear to be largely neutral with respect to selection. That is precisely why they are powerful tools for the study of natural history. Patterns of differentiation and migration are permanently recorded in the genes with relatively modest influence from natural selection superimposed. The large isozyme differences noted between North Coastal populations could have resulted from survival in separate refugia or survival in a single refugia either in the north or south with founder's effects accounting for the differences. The latter explanation seems unlikely considering the number of rare alleles present and the relatively high levels of variability found throughout the region. Consequently we conclude the two patterns of variation observed in very different sets of traits actually reinforce one another in support of a north coastal refugium (ia).

Provenance data may also be considered in support of a Yukon refugium. Hagner (1970) studied several characteristics on two-year-old seedlings that indirectly measured cold tolerance. Two Yukon sources from within or near the unglaciated region of the Territory consistently differed from seedlings of other far-northern sources. They possessed greater cold hardiness.

Palynological support for a Yukon refugium is lacking (reviewed by Wheeler and Guries, 1982a; and Critchfield, 1984). However, relatively few sites have been studied, especially within the zone that was unglaciated. If lodgepole pine had persisted throughout the Wisconsin, it probably did so in very small isolated patches that would be hard to capture through pollen core sampling. Another interesting theory is that lodgepole pine may have survived long periods of severe climatic conditions as cached seed. Edo Nyland (personal communication, 1978) reports the recent establishment of a small lodgepole pine stand on a disturbed site well north of the established species range in the central Yukon. He believes pine seed was preserved in the permafrost until exposed by road grading operations. Fire, which blackens the soil surface, thus increasing heat buildup and thawing, may have the same effect. Thus, seed stored for years in the permafrost could sprout and create a new forest long after a local extinction event.

Whether the species survived in place as a forest or as seed in cryogenic storage, a fairly strong case can be built, based upon circumstantial genetic evidence, that lodgepole pine persisted in far northern refugia both on the coast and in the interior.

Subspecies *latifolia* populations surviving in northern refugia probably recolonized most of the Yukon and extended south in British Columbia where it was met by pine moving north, probably within a few hundred kilometers of the border (fig. 9).

Pine migrating north from a major southern refugium probably disseminated from two or more isolated centers. One center occupied an area west of the Rockies (Mack *et al.*, 1978) and colonized the central interior portion of British Columbia by migrating along the structural intermountain valleys of the province. The other main center was probably located in western Montana and Wyoming with migration northward occurring along the east and west flanks of the Rocky Mountains.

Along the coast, pine populations probably spread from one or more isolated sites. In addition to the Queen Charlottes Islands, (Warner *et al.*, 1982) possible north-coastal refugia in-

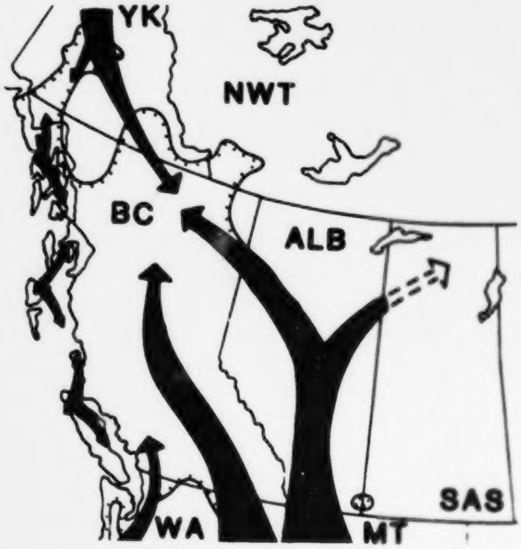


Figure 9. – Putative migratory pathways for lodgepole pine following Pleistocene glacial retreat.

clude unglaciated coastline of lodgepole pine, from Glacier Bay to the Yakutat Peninsula (Coulter *et al.*, 1965; Derksen, 1976).

The biogeography of lodgepole pine in the Rocky-Mountain-Intermountain region and in the Sierra Nevada is probably much less eventful and certainly less well studied than in the areas to the north. The ssp. *murrayana* is the most distinctive in the species and it would appear as though it has evolved essentially in place, isolated from the other subspecies, for many thousands of years. The many populations of ssp. *latifolia* found throughout the American Rockies from Montana to Colorado are not as differentiated as one might expect if they had evolved as independent entities during the Pleistocene. Moore (1981) showed these populations to vary clinally for many morphological and growth traits, with southern Colorado populations the most distinctive. He found large within-population variation for most traits studied. These results argue for a certain continuity of species distribution throughout the Rocky Mountain region during the last full glacial. A parallel argument has been developed for bristlecone pine (*P. longaeva*) in the Great Basin, using isozyme data (Hiebert and Hamrick, 1983).

Perhaps the most interesting portion of the species American distribution, biogeographically speaking, is the area ranging north and east from the Siskiyou Mountains in south central Oregon. Vestiges of both spp. *murrayana* and *latifolia* are found in populations from the Cascades to the Blue Mountains (Wheeler and Guries, 1982 b; Smith, 1983). More work is needed to better understand the population structure of lodgepole pine in this region.

SUMMARY

Lodgepole pine is a widely distributed and highly variable species native to western North America. It is comprised of three, well differentiated, interfertile geographic races or subspecies and at least one additional edaphic ecotype that has received subspecies status in the past. The races differ from one another in a number of traits including tree longevity, dimensions, form, and branchiness; needle, seed, and cone characteristics; and biochemical markers.

Several botanical traits that could potentially impact individual tree and stand productivity are noted. These "components of yield" include seed germination vigor, root nutrient uptake efficiency, and crown form.

Patterns of variation in various morphological and biochemical traits are used to make predictions about the biogeography of lodgepole pine. It is proposed that the northern races of the species survived Pleistocene glaciation in one or more northern refugia in addition to occupying areas south of the continental ice sheets.

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LODGEPOLE PINE AS A COMMERCIAL RESOURCE IN THE UNITED STATES

Dwane D. Van Hooser
and
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ABSTRACT

Lodgepole pine (*Pinus contorta* Dougl. ex Loud.) has contributed greatly to the early economic development of the northern and central Rocky Mountain regions. In the last decade annual lumber production from lodgepole pine has averaged between 2.5 and 3.5 Mm^3 (500 and 700 million board feet). Lodgepole currently accounts for 1 percent of the nation's total lumber output. In the Rocky Mountain States it accounts for 16 percent of the annual lumber harvest; on a state-by-state basis it accounts for between 20 to 70 percent. Currently, there are approximately 8,000 jobs associated directly, or indirectly, with lodgepole pine processing in the region.

INTRODUCTION

Lodgepole pine has probably been used "commercially" since it began to coexist with man. We know that the species was used by native Americans for tepee, travois, and corral poles. And the first white men to venture into the northern Rocky Mountains probably found lodgepole a readily available source of material for cabins and more primitive shelters. We also know that lodgepole has been closely related, if not key, to the settlement and development of the western United States. In his epic novel "Centennial," James Michener (1974) alludes to the use of the species by "Our People." The great warrior Lame Beaver makes a journey to Blue Valley in search of new "lodge" poles. While there he discovers a strange yellow metal that can be pressed into bullets without being melted. The story of these yellow bullets spreads far and wide and, so the story goes, eventually leads to the Colorado gold rush of 1858-59. One cannot conclude that lodgepole was totally responsible for the gold rush, but because of its use and uniqueness it could be assumed to have contributed to the discovery of gold.

HISTORIC USE

Lodgepole contributed in many ways to the development of the mining industry in the Rocky Mountain West. In the early days, when small placer mines predominated, much of the sparse volume of lumber needed for sluice boxes and buildings was almost certainly supplied by lodgepole pine. As attention shifted to silver and then to copper, the mining industry moved from small placer operations to "quartz mines." These required significant excavation and large smelters typified by those of Butte, Montana. Lodgepole pine was a major source of fuel for such smelters and also provided timber for the mines.

As more and more people came West by wagons or shank's ponies, the demand for faster and more comfortable transportation increased and finally led to the construction of the first transcontinental railroad. This subsequently led to another period of commercialization for lodgepole pine. Because of its ubiquity in the central and northern Rockies, the ties underlaying many miles of rails in this area were probably hand-hewn lodgepole. The number of ties used in building the transcontinental railroad probably ran into the millions.

During the 1800's lodgepole pine was a species of convenience. It was heavily used because it was abundant. Physical properties had little to do with its utilization with the possible exception of tepee poles. Use of lodgepole probably peaked in the late 1800's, with production gradually tapering off until the immediate postdepression years. This trend is apparent in statistics on lumber production that became available for lodgepole in the early 1900's (Steer, 1948).

From 1909 until 1933 lodgepole lumber production was generally in decline (fig. 1), much the same as total lumber production for all species nationwide. From 1933 until about 1959, the production trend was upward, increasing from 49,000 m^3

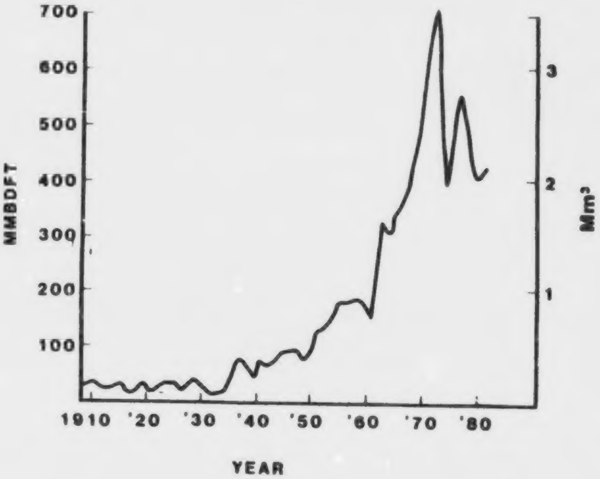

Figure 1.—Lodgepole pine lumber production in the United States by year. (Source: Steer, 1948, Western Wood Products Association Annual Reports.)

(10 million board feet) annually to almost 941,000 m^3 (190 million board feet). Over the next 15-year period the production of lodgepole pine lumber increased exponentially, finally reaching an all-time high of more than 3.5 million m^3 (700 million board feet) in 1973. Then, following the trend set by the national economy, production declined sharply falling to less than 2.0 million m^3 (400 million board feet) in 1975. Since then production has fluctuated, but has generally averaged between 2.5 and 3.5 million m^3 (500 and 700 million board feet).

CURRENT USE

Today lodgepole pine is primarily a lumber species. In recent years lumber manufacturing has consumed 80 to 90 percent of the lodgepole pine timber converted into primary products. It is currently used, however, to produce a wide range of products, including railroad ties, plywood, posts, poles, house logs, and pulp, paper, and reconstituted products. In addition, lodgepole is being used more and more for remanufactured products such as paneling and finger joined moulding. And, thanks to the mountain pine beetle, lodgepole pine is still a common source of fuelwood.

The plywood industry historically has used only very small volumes of lodgepole pine, but use is presently increasing. The manufacturing of other products such as house logs, utility poles, and posts accounts for less than 10 percent of the total utilization of the species (Keegan, 1980; Keegan, *et al.*, 1983).[1] But these operations can be very labor intensive and often have high levels of employment per unit volume of output.

This increase in the use and current level of production is rather significant for lodgepole pine, but it is barely a blip on the national scale (fig. 2). From a national perspective, lodgepole's relative position in the timber products arena really hasn't changed much. In 1933, product output from lodgepole pine amounted to less than 1 percent of the nation's total (Steer, 1948). In 1976, the latest year when removals data for all states and all species were available, roundwood output from lodgepole pine was about 3.3 million m^3 (116 million cubic feet) still just slightly less than 1 percent of the nation's total (USDA Forest Service, 1982).

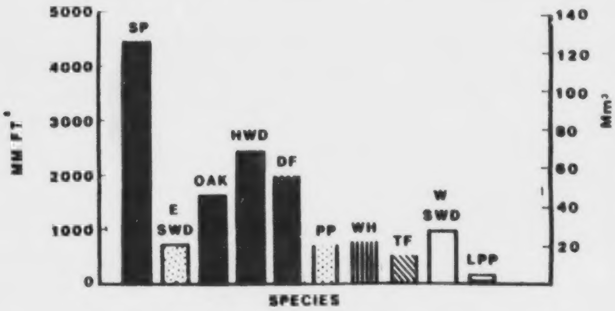

Figure 2.—Annual removals from growing stock inthe United States by species, 1976. (Source: USDA, 1982; SP = southern pine, ESWD = eastern softwood, HWD = hardwood, DF = Douglas-fir, PP = ponderosa pine, WH = western hemlock, TF = true fir, WSWD = western softwood, LPP = lodgepole pine.)

Regional, National, and Local Trends

If we look at lodgepole's output regionally, we see several emerging trends. First, lodgepole is being harvested nearly in proportion to its occurrence—the reversal of a long-standing trend. For example, in 1977 lodgepole accounted for 23 percent of the total softwood growing stock in the northern Rocky Mountains and 16 percent of the annual removals in the region (USDA Forest Service, 1982). This represents a significant increase in removals over 1970 (USDA Forest Service, 1973) and nearly a fivefold increase since the 1950's when lodgepole utilization began to trend upward. The amount of material being harvested as compared to annual growth is also increasing. In the 1950's only about one-fifth of the net annual growth of lodgepole was being harvested (Wikstrom, 1957). Today that figure is closer to two-thirds.

Another trend that emerges is a preference for lodgepole for conversion to industrial roundwood products. As recently as 1969, lodgepole pine's contribution to product output in the Rocky Mountain region was well behind Douglas-fir, ponderosa pine, western white pine, and western larch (Setzer, 1971 a, b, c, d). Today, lodgepole is second only to Douglas-fir (USDA Forest Service, 1982) (fig. 3). Moreover, based on current trends, it is conceivable that lodgepole could soon become the number one species used for roundwood product conversion by forest industries in the northern Rockies.

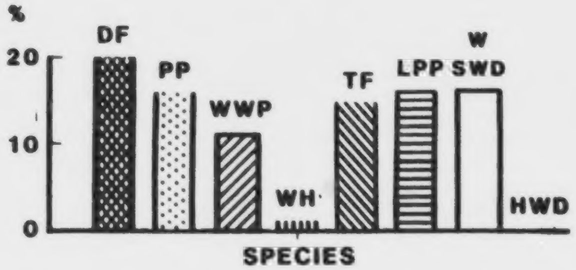

Figure 3.—Annual removals from growing stock in the Northern Rocky Mountain States, 1976. (Source: USDA, 1982; DF = Douglas-fir, PP = ponderosa pine, WWP = western white pine, WH = western hemlock, TF = true firs, LPP = lodgepole pine, WSWD = other western softwood, HWD = western hardwood.)

Other significant trends are emerging in Montana. In the early 1900's lodgepole was consumed only incidentally, that is, if it was convenient it was harvested, but lumbermen were not prone to "seek it out." In the 1960's lodgepole began to emerge as a bona fide timber species. Harvest data from 1969 (Setzer, 1971 a, b, c, d) indicate that lodgepole accounted for 12 percent of the total harvest. Subsequent mill canvasses found that lodgepole's share of the timber harvest had increased to 21 percent in 1976 (Keegan, 1980) and 25 percent in 1981 (Keegan *et al.*, 1983). In addition, these studies revealed that the absolute volume of lodgepole harvested was increasing while the total timber harvest was actually declining (fig. 4).

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[1] These reports and similar information were generated by the Forest Industry Data Collection System which was developed jointly by the University of Montana, Bureau of Business and Economic Research, and the Intermountain Station Forest Survey Research Work Unit.

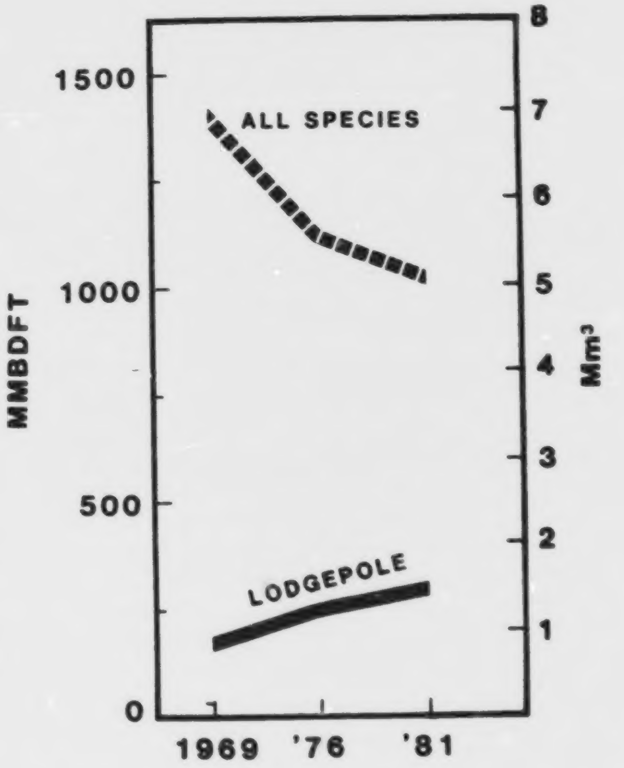

Figure 4.—Timber products output from all species and lodgepole pine in Montana by year. (Source: Setzer, 1971 c; Keegan, 1980; Keegan *et al.*, 1983.)

The 1981 industry canvass in Montana (Keegan *et al.*, 1983) also revealed that lodgepole pine accounted for 31 percent of the saw log harvest, 24 percent of the pulpwood harvest, and 74 percent of other roundwood products harvest—thus becoming the dominant species in these three product areas. Veneer logs was the only roundwood product where lodgepole was not the star performer.

To sum up, in Montana at least, if not in the northern Rocky Mountain region, lodgepole has arrived and is truly a species to be reckoned with. What has caused this phenomenal growth in the consumption of lodgepole and what impact has this growth had on the four lodgepole states in the Rocky Mountain region?

During the 1973 Lodgepole Pine Symposium, Bob Benson (1975) made a few remarks relative to the future utilization of lodgepole pine that are worth repeating. Benson said that stumpage prices would have little or no effect on the future harvest and utilization of lodgepole. Further, he said utilization and harvesting would be determined by criteria such as advancing sawmilling technology and the evolution of wood products' markets where species would not be particularly important. Benson's predictions have indeed come to pass.

Sawmilling technology has advanced to the point where small logs, such as those characteristic of lodgepole, can be processed at a profit. More advances within the last decade have included the computerization of log breakdown systems. This combined with thin-kerf sawing and reduction in sawing variation has boosted lumber recovery while allowing mills to improve production rates. These adavances are designed to handle small, smooth logs and can process upwards to 5,000 logs per 8-hour shift. Because lodgepole produces a relatively smooth bole when peeled, these types of headrigs seemed ideal for processing the species. Moreover, because recovery from these systems is so favorable, tolerances that were once measured in 1/8 and 1/16 of an inch are now being measured in thousandths of an inch.

Lodgepole pine's acceptance as a commercial lumber species has also been enhanced by advances in drying technology. Not too long ago many foresters thought that lodgepole's scientific name—*Pinus contorta*—related to lumber that came from the species. Those corkscrew-like 2x4's were almost given away at the local hardware store or lumberyard under the euphemism "poor boy studs." Through the application of new drying procedures and more strict compliance to Western Wood Products Association specifications, studs are now being produced that are free of warp and twist. Lodgepole studs are beginning to be marketed with "white woods"—the classification that also includes the true firs, spruce, and occasionally ponderosa pine. Lodgepole is beginning to lose its reputation as the bad guy in the construction industry.

The forest products industry no longer views lodgepole pine as an inferior or undesirable species, and its acceptance in the marketplace has continued to improve. It is actually being favored over some traditional species because it dries well, it is light, and it contains small, tight knots.

Economic Importance

Approximately 4,000 workers in the western United States are directly employed in the harvesting and primary processing of lodgepole pine timber into lumber and other wood products. In monetary terms, this equates to about $80 million.

Further, these jobs support an estimated additional 4,000-6,000 positions in areas such as retail sales. We estimate conservatively, therefore, that harvesting, processing, and distributing of lodgepole pine products provides 8,000-10,000 total jobs and contributes some 150-200 million dollars to local economies. Jobs such as those in the construction industry which are based on further utilization of lodgepole pine lumber would increase this figure.

In spite of these lofty figures, however, lodgepole pine does not have a significant impact on the economy from a national perspective. The harvesting and primary processing of timber products into lumber, wood products, and paper employs approximately 1.4 million workers in the United States (USDC, 1982). In comparison, the few thousand workers employed in processing lodgepole pine seem insignificant. Just as the loss of the several hundred million board feet of lodgepole lumber produced annually would not create much change in the total annual national lumber consumption, the loss of eight to ten thousand jobs would go unnoticed in the national employment statistics.

Within the Rocky Mountain region, however, the employment generated by lodgepole pine and the subsequent contribution to local economies has considerable significance. Lodgepole pine is an important part of the raw material base for the wood products industry in much of the northern and central Rocky Mountains. And the wood products industry is a major component of the economic base of the four northern Rocky Mountain states.

Lodgepole pine's contribution to the industry has its largest statewide economic impact in Montana. There the wood products industry is a significant economic sector, accounting for 10 to 15 percent of the state's nonfarm economic base, and lodgepole pine provided 25 percent of the timber processed in 1981.

The economic impact of lodgepole pine on a more localized area has again been most apparent in Montana. In Montana's major timber-producing regions – the seven western counties (Lincoln, Flathead, Sanders, Lake, Mineral, Missoula, and Rivalli) – wood products is the major industry. It accounts for 40 to 50 percent of the area's economic base and directly employs 7,000-9,000 workers. Since 1969 the harvest of all major species in these counties has declined, with one exception. The volume of lodgepole pine harvested and processed has more than doubled – from 426 km^3 (86 million board feet) in 1969 to more than 892 km^3 (180 million board feet) in 1981. In 1981 lodgepole pine provided more than 20 percent of the timber harvested in the seven counties in comparison to 1969 when it accounted for less than 10 percent. Without the increasing contribution of lodgepole pine, the economy of western Montana would have suffered considerably in the past 15 years.

There are many small geographic areas and communities in the Intermountain West that depend heavily on lodgepole pine for economic well-being. For example, Jackson County, Colorado, has a population of only about 2,000 people. But in recent years, the harvesting and processing of lodgepole pine has provided employment either directly or indirectly for between 100 and 300 workers. This is certainly a major contribution to the local area economy.

CONCLUSION

Lodgepole pine has been important to the "economy" of the Rocky Mountain West since before the arrival of European man. Today it has developed into a major regional lumber species and has been essential to maintaining the wood products industry as a key component of the economic base within the Intermountain West.

Note: Conversion factors used in this paper are:
one cubic meter = 35.3145 cubic feet
one thousand board feet Scribner rule = 175 cubic feet
one thousand board feet Scribner rule = 4.9555 cubic meters
Source: USDA Forest Service, 1982

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LODGEPOLE PINE AS A COMMERCIAL RESOURCE IN CANADA

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ABSTRACT

Volumetrically, lodgepole pine ranks second among species harvested in B.C. and Alberta, exceeded only by the spruces. Although it comprises only 15 percent of the mature standing timber in B.C. and 20 percent in Alberta, it accounts for 20 and 40 percent of the annual harvest in these respective provinces. Stumpage value of lodgepole pine in B.C. is the lowest of the ten species commonly harvested, owing mainly to its small piece size.

The value of shipments of forest products made from lodgepole pine is estimated at $2.4 billion for 1982. In the lumber form it is sold in the Spruce-Pine-Fir group (SPF), while its veneer appears in plywood as Canadian Softwood Plywood (CSP). It supplies pulpwood largely as chips in B.C., while in Alberta, the major form of pulpwood is in the roundwood form. Poles, ties, mechanically stress-rated lumber, and remanufactured items round out the list of other products produced from lodgepole pine.

VOLUMES AND HARVESTS

In Canada, lodgepole pine extends over B.C., Alberta and the Yukon. Most of the trees of merchantable size are in B.C., which contains about 80 percent of Canada's total merchantable volume (table 1). If the differing specifications for utilization standards shown in table 1 are taken into account, the overwhelming proportion of larger commercial trees (greater than 17.5 cm dbh) occurs in B.C. Within B.C., 80 percent of the mature volume occurs in three regions – Prince George, Bulkley-Northwest and Cariboo (fig. 1).

Lodgepole pine accounts for 15 percent of the total standing volume of mature timber in B.C., and 20 percent of the Alberta total. Because of the significant hardwood volume in Alberta, lodgepole pine actually accounts for 37 percent of the total mature coniferous volume of that province.

Over the past decade, the timber harvest of lodgepole pine has increased (table 2). The average for the past five years (1978-82) has exceeded that of the previous five years (1973-77) by 31 percent. Part of this increased harvest of lodgepole pine is undoubtedly due to salvage operations in stands heavily attacked by the mountain pine beetle. Lodgepole pine currently represents about 20 percent of the total annual timber harvest in B.C., and 40 percent of the Alberta total. Thus in both provinces, the harvest is proportionately in excess of the inventory figures. Among other species or species groups, only the spruces contribute a greater volume than lodgepole pine to the timber harvest in B.C. and Alberta.

Table 1. – Mature timber volume for lodgepole pine in Canada

Origin	Volume (MMm^3)	Utilization diam. (cm)
British Columbia – Total	1,246	17.5 b.h. 10.2 top
Peace River region	73	
Prince George region	336	
Bulkley – NW region	366	
Nelson region	45	
Kamloops region	124	
Cariboo region	294	
Prince Rupert region	6	
Vancouver region	3	
Alberta – Total (excludes Metis colonies, Indian reserves, federal parks and wilderness areas)	287	13.0 stump 7.0 top
Yukon – Total	64	9.1 b.h. 7.6 top
CANADA – TOTAL	1597	as stated

Sources:
- B.C. Ministry of Forests. 1980. Forest and Range Resource Analysis Tech. Report.
- Alberta Forest Service Div. 1968. Alberta Forest Inventory.
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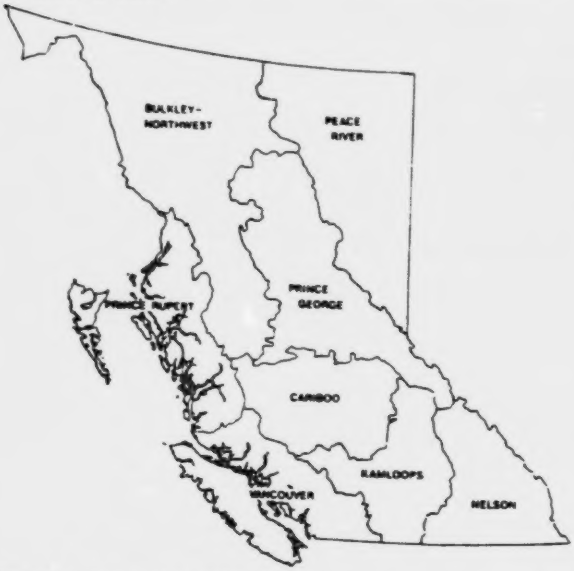

Figure 1. – Forest analysis regions in B.C.

Table 2. – Annual timber harvest for lodgepole pine in B.C. and Alberta

Year	B.C.		Alberta	
	Volume (Mm^3)	% of total harvest	Volume (Mm^3)	% of total harvest
1973	9,118	13	1,822	41
1974	8,438	13	1,872	45
1975	7,872	14	1,763	43
1976	11,298	16	1,920	43
1977	13,252	16	2,086	43
1978	13,819	19	1,920	41
1979	14,788	18	2,358	41
1980	14,347	19	2,173	40
1981	12,272	19	2,156	39
1982	11,929	21	2,156	39

Sources:

- Council of Forest Industries of B.C. 1983. Statistical tables.
- Alberta Forest Service Div. 1984. Table A6: Ten-Year Production Summary. (Mr. D. H. Fregen, Director, Timber Management Branch).

The stumpage price for lodgepole pine in B.C. is the lowest of ten species or species groups reported (table 3). Therefore, although lodgepole pine ranks second in volume harvested, it places no better than sixth among species in total value received from sales. The leading contributors to its low stumpage value are its small tree and log size and the need to salvage beetle-killed timber.

Table 3. – Stumpage prices and total value received from sales in B.C., 1982-83

Species	Price ($/m^3)	Total value ($)
Balsam fir (*Abies* ssp.)	1.78	9,722,000
Cedar (*Thuja plicata*)	3.05	11,983,000
Cypress (*Chamaecyparis nootkatensis*)	9.31	2,653,000
Douglas-fir (*Pseudotsuga menziesii*)	2.29	9,389,000
Hemlock (*Tsuga heterophylla*)	2.42	14,885,000
Larch (*Larix occidentalis*)	1.22	330,000
Lodgepole pine (*Pinus contorta*)	0.84	9,385,000
Spruce (*Picea* spp.)	1.63	22,298,000
White pine (*Pinus monticola*)	1.99	287,000
Others	1.16	167,000

Source: B.C. Ministry of Forests. 1983. Annual Report, 1982-83.

PRODUCTS

Table 4 indicates the importance of lodgepole pine to the forest products industry in B.C. and Alberta. Lumber is the most important single product, with Canadian production close to 3 billion fbm. It is marketed almost exclusively in the spruce-pine-fir (SPF) species group, so accurate figures on amounts of lodgepole pine alone are difficult to obtain. Over the past decade, yearly average prices for kiln-dried 2 x 4 random length SPF, FOB mill, have ranged from U.S. $117 per M fbm in 1975 to $225 in 1979. Forecasts for the next four years indicate an improvement to the $300 level in 1986 (Widman Management Ltd., 1984).

Table 4. – Lodgepole pine production as percentages of Provincial totals for all species

	B.C.	Alberta
	(percent)	
Mature timber volume	15	20
Lumber produced	15	35
Pulpwood supplied (chips & roundwood)	15	45
Poles produced (by number)	35	100*
Railway ties produced	90	100*
Veneer produced for plywood	10	20

*including some jack pine (*Pinus banksiana* Lamb.)

Source: Industry estimates and sources quoted in table 2.

An increasing volume of SPF is being graded by mechanical stress-rating (MSR) machines. Presently, seven mills in B.C. and Alberta are producing MSR lumber, with an estimated capacity of 160 million fbm (Woodbridge, Reed and Associates, 1982). Since lodgepole pine has a slightly higher average density and strength than the other species in the SPF group, mills with a high proportion of lodgepole pine in their SPF mix can generally recover greater quantities of high E/f grades. These mills may then realize an average premium of $15-30/M fbm compared to their former visual grading. The MSR grading of SPF is especially attractive because of the higher stress values that can be assigned, compared to traditional visual grading. MSR lumber is marketed in Canada and the U.S. for factory manufacture of pitched roof trusses, flat floor trusses, and other engineered construction.

Most of the lodgepole pine supplied for pulpwood in B.C. is in the form of sawmill residual chips. In Alberta, almost half of the total pulpwood supplied is lodgepole pine, and about 60 percent of this is delivered in the roundwood form. In B.C., current prices of chips from SPF mills are about $40 per bone dry unit, but this price could double within the next few years as the pulp market strengthens.

Lodgepole pine is used along with other inland species in B.C. and Alberta to manufacture Canadian Softwood plywood (CSP) for sheathing. Production of CSP now exceeds that of Douglas-fir plywood, and amounts to about one billion square feet (3/8 inch basis). It faces stiff competition from waferboard and oriented strand board, and is not expected to show a significant increase in production as a consequence. In fact, a $35 million wafer board plant has just been announced for the southern Interior of B.C., operating on an annual harvest of 160,000 m^3 of "small stagnant" lodgepole pine.

Lodgepole pine sapwood treats well with wood preservatives in standard pressure processes. This, coupled with its straight form, makes it a preferred pole species. Practically all distribution poles up to about 45 feet in the Interior of B.C. and Alberta are lodgepole pine. While other species (western redcedar, Douglas-fir) are utilized in B.C., especially for longer poles, the only indigenous pole species in Alberta is lodgepole pine, along with its close relative, jack pine.

Although lodgepole pine heartwood treats more poorly than its sapwood, it remains by far the outstanding species for railway tie production, owing to its availability and hardness in combination with its modest treatability, which is enhanced by incising.

Finally, there is a trend emerging for the remanufacture of lodgepole pine lumber into special wood products. Lodgepole pine is third, behind western hemlock and western redcedar in B.C. for value-added remanufacturing. Successful items include thin panelling (1/4 in x 4 in x 6 to 8 ft), edge-glued shelving and pre-stained siding. The panelling is all knotty-grade, resawn from 1 in x 4 in side-cut lumber produced by stud mills, whereas the siding is derived by resawing two-inch dimension. Almost all of these products are marketed within Canada. Other items that have been made sporadically include "Scandinavian" furniture components in the form of tabletops and rails, and joinery graded by Scandinavian rules for the U.K. market. These products currently are not produced owing to the devalued Swedish kroner. Nevertheless, the hardness and knot structure of lodgepole pine make it attractive for remanufacture, if well-dried, stress-free lodgepole pine lumber is available.

In summary, lodgepole pine has a critical commercial significance in Canada. On the basis of lumber and plywood alone, it accounts for mill shipments valued at $600 million (assuming $200/M bd.ft lumber or M sq.ft. plywood). Since lodgepole pine represents about 11 percent of the total Canadian timber harvest, which when converted into products had an estimated shipment value of $21.9 billion in 1982 (Canadian Forestry Service, 1984), a final annual value of lodgepole pine products can be estimated at $2.4 billion.

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PHYSIOLOGY AND GENETICS

SELECTED PHYSIOLOGICAL CHARACTERISTICS OF LODGEPOLE PINE

John H. Bassman

ABSTRACT

Lodgepole pine is among the most intensively studied of our western conifers, yet comparatively little is known of its basic physiology. This paper reviews available information on vegetative physiology of lodgepole pine.

Maximum photosynthetic rates reported are 10 mg CO^2 dm^{-2} h^{-1} with light saturation at about 380 W m^{-2}. Temperature optimum for photosynthesis is about 20°C. Leaf area is linearly related to sapwood basal area with maximum Leaf Area Indices of 14.0 m^2 m^{-2}. Stomata of lodgepole pine are very sensitive to moisture deficits, closing at -1.46 MPa. Leaf conductance is related to predawn xylem sap potential with maximum conductance reported to be 0.40 cm s^{-1}. Roots of lodgepole pine are resistant to flooding and show anatomical adaptations to high water tables. Compared to other western species, lodgepole pine is intermediate in resistance to SO_2 fumigation but highly sensitive to fluoride emissions.

INTRODUCTION

Tree growth is a function of genetic makeup in combination with environmental influences acting through physiological processes. If we are to manipulate tree growth advantageously, we must understand these physiological processes and show they are affected by environment and genetics (Kramer and Kozlowski, 1979). The objective of this paper is to review literature pertaining to vegetative physiology of lodgepole pine (*Pinus contorta* Dougl. ex Loud.). Recent bibliographies (Lotan and Sweet, 1975; Reid Collins, 1983; Tackle and Crossley, 1953) list nearly 3000 citations. Yet, for the most part, reports addressing the basic physiology of lodgepole pine are few. The exception is water relations physiology which has received considerable attention the past 10 years.

Major topics of this paper are photosynthesis, leaf area attributes, water relations, carbon allocation, and responses to environmental stresses. No attempt is made to review phenological, morphological, or anatomical characteristics of lodgepole pine, as these have been given adequate treatment elsewhere (Lanner and Van Den Berg, 1975; Owens and Molder, 1975; Pharis *et al.*, 1975). Owens and Molder (1984) have recently completed a review of reproductive functions in lodgepole pine.

PHOTOSYNTHESIS

Plant growth is ultimately dependent on CO_2 fixation by photosynthesis (PS). Many factors affect this process, including light, temperature, CO_2 concentration, water supply, humidity, wind velocity, and phenology (Larcher, 1969). These processes do not act independent of one another in their control of PS so it is often difficult to sort cause and effect. Some of these factors (e.g., water supply, light, humidity, wind) act on PS through stomatal action.

Effects of Light

Lodgepole pine is similar to most other conifers and C_3 plants in general in its photosynthetic responses to light. PS increases with increasing light intensity up to a saturation point after which further increases in light intensity do not increase PS (Fig. 1). Dykstra (1974) observed light saturation at around 380 W m^{-2} for 2-year-old seedlings grown in a greenhouse. But in another study (Ronco, 1970), two-year-old seedlings grown outside at 2744 m elevation in Colorado were apparently not saturated even at 12,000 ft-c (about 543 W m^{-2}). These values are high by comparison to other western conifers (Table 1). Dykstra (1974) reported a light compensation point at about 6-10 W m^{-2}.

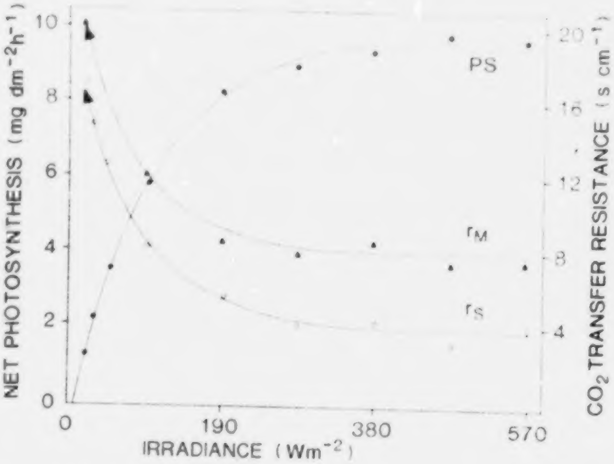

Figure 1. – Influence of light intensity on net photosynthesis (PS) and on stomatal (r_s) and total mesophyll (r_m) resistances to CO_2 transfer. Measured at 20°C needle temperature (from Dykstra, 1974).

Effects of Temperature

Conifers generally show a wide range over which temperatures are optimum for PS (Larcher, 1969). The temperature optimum in lodgepole pine is about 20°C (Dykstra, 1974; Scott, 1970) (Fig. 2). These temperatures compare to a range of 10 to 25°C reported for Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) (Lassoie, 1982) and 18°C for ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) (Helms, 1976).

Photosynthesis in lodgepole pine is sensitive to low temperatures. In cold weather, lodgepole pine shoots brought

Table 1.—Light intensities for saturation of photosynthesis in several western conifers (values are approximate due to conversion of units).

SPECIES	IRRADIANCE ($W\ m^{-2}$)	SOURCE
Douglas-fir	130	(Lassoie, 1982)
Ponderosa pine	130	(Helms, 1976)
Subalpine fir	169	(Knapp and Smith, 1982)
Engelmann spruce	174-217	(Ronco, 1970)
Lodgepole pine		
greenhouse	380	(Dykstra, 1974)
field	>543	(Ronco, 1970)

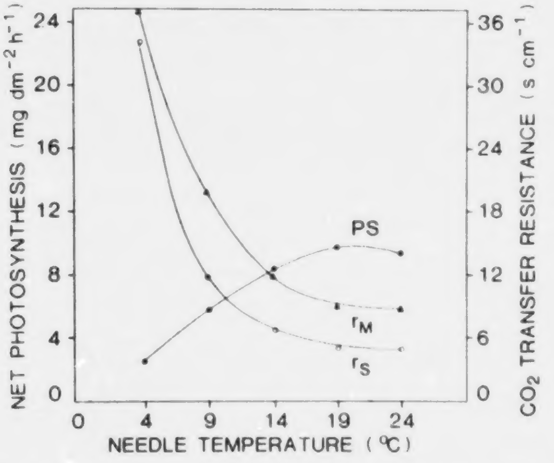

Figure 2.—Effect of needle temperature on net photosynthesis and stomatal (r_s) and mesophyll (r_m) resistances to CO_2 transfer. Measured at 570 $W\ m^{-2}$ irradiance (from Dykstra, 1974).

inside took up to 75 h to reach the compensation point and never reached a level of PS comparable to summer even after 10 days (Schwarz, 1971). By comparison, Douglas-fir was able to rapidly resume PS activity when brought into warmth, reflecting its greater ability to make use of warm spells in winter, photosynthesize later in the fall and earlier in spring than lodgepole pine. The inability of lodgepole pine PS to function at cold temperatures is at least partially due to the effects of low temperature on stomatal function (see later text and Fahey, 1979).

Effects of Moisture Stress

The effects of moisture stress on PS are mediated through stomatal response. Lodgepole pine stomates are sensitive to moisture stress compared to its common western associates. Brix (1979) studied the effects of soil drying on PS in seedlings of Douglas-fir, western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), white spruce, and lodgepole pine. Lodgepole pine was the most sensitive to increasing water stress, reaching a threshold shoot water potential (ψ_s) for decline in PS below 100% at −0.66 MPa; (Table 2). Net PS became 0 at −2.24 MPa, also higher than for the other species. Dykstra (1974) reported 0 PS at −1.5 MPa. These results are similar to those reported by Morris and Tranquillini (1969).

Species and Provenance Comparisons

Rates of PS in lodgepole pine have been compared to those of other species by several investigators. At saturating light intensities (>1500 lumens ft^{-2}), 1-year-old seedlings of lodgepole pine had PS rates higher than Austrian pine (*Pinus nigra* Arnold [Reise Mariazell]), but lower than Monterey pine (*P. radiata* D. Don) (van den Driessche and Wareing, 1966). PS rates are apparently higher in lodgepole pine than mountain beech (*Nothofagus solandri* var. *cliffortoides* [Hook f.] Poole) and mugo pine (*Pinus mugo*) but less than in European larch (*Larix decidua* Mill.) (Benecke *et al.*, 1977; Scott, 1970). In comparisons by Benecke *et al.* (1977) water use efficiency (WUE), the amount of CO_2 fixed per g water transpired, was highest in lodgepole pine (14 mg $CO_2\ g^{-1}\ H_2O$) and lowest in mugo pine (11 mg $CO_2\ g^{-1}\ H_2O$).

Intraspecific variation in PS rates has also been demonstrated. Sweet and Wareing (1968) reported significant differences in net PS and respiration between four provenances at all light intensities tested and at a constant temperature of 20°C. Those provenances with high rates of PS also had high rates of respiration. Light saturation and compensation points were about the same in all provenances.

A summary of photosynthetic attributes of lodgepole pine is presented in Table 3.

Table 2.—Rates of net photosynthesis based on a unit of leaf area and leaf dry weight with soil water at field capacity (100% rate) and threshold plant water potentials for rates of 100, 50 and 0% (from Brix, 1979).

	100% rate, mg CO_2 h − 1		Water potential threshold, MPa		
Species	per dm^2	per g dry wt.	P_N, 100%	P_N, 50%	P_N, 0%
Douglas-fir	10.4 b	13.3 c	−1.00 b	−1.83 b	−5.39 c
Western hemlock	8.0 a	12.5 c	−1.07 b	−1.84 b	−3.97 bc
White spruce	15.6 c	9.1 b	−1.24 c	−1.73 b	−2.86 b
Lodgepole pine	9.6 b	6.1 a	− .66 a	−1.25 a	−2.24 a

NOTE: Values in the same column followed by the same letter are not significantly different (P=0.05).

Table 3.—Photosynthetic attributes of lodgepole pine.

			SOURCE
Maximum Rates:	10	mg CO_2 dm^{-2} h^{-1}	(Dykstra, 1974)
	12	mg CO_2 g^{-1} DW h^{-1}	(Sweet and Wareing, 1968)
Light Saturation:	380	W m^{-2}	(Dykstra, 1974)
Light Compensation:	6-10	W m^{-2}	(Dykstra, 1974)
Temperature Optimum:	20	°C	(Dykstra, 1974; Scott, 1970)
ψ_s for PS Reduction:	−0.66	MPa	(Brix, 1979)
ψ_s at 0 PS:	−2.24	MPa	(Brix, 1979)

LEAF AREA CHARACTERISTICS

Relation to Site Water Balance

Plant productivity is a function of instantaneous and cumulative rates of PS as well as the amount of photosynthesizing leaf area. Evidence suggests that maximum leaf area of a community is mechanistically controlled by site water balance in water-limited environments, rather than the species making up the community (Gholtz, 1982; Grier and Running, 1977).

At the individual plant level there is a partitioning or competition for the available leaf area. The "pipe model" theory (Shinozaki *et al.*, 1964a; Shinozaki *et al.*, 1964b) suggests that a unit of foliage is serviced by a specific cross-sectional area of conducting sapwood in the crown, resulting in a strong correlation between leaf area and sapwood basal area (Waring *et al*, 1982). Recent work demonstrates that the "pipe model" theory is applicable to many conifers, including lodgepole pine (Grier and Waring, 1974; Kaufmann and Troendle, 1981; Waring *et al.*, 1982). The exact relationship of leaf area to sapwood varies by species. In comparison to many other conifers (Table 4), the ratio of leaf area to sapwood basal area in lodgepole pine is low.

Leaf Area and Leaf Area Index

Surface area of individual leaves is needed to express a variety of gas exchange parameters and for per tree and per hectare estimates of leaf area. Determination of leaf area in conifers is a difficult task and several methods have evolved to estimate leaf area. Drew and Running (1975) showed that a glass bead technique was more accurate than an optical planimeter and suggested the former as a superior method for pines. Needle volume is more easily attained than needle area by using simple volumeters (Ronco, 1969). Lopushinsky (1970) reported a high correlation (r = 0.98 for lodgepole pine) between needle surface area and needle volume in ponderosa and lodgepole pine. For pines with needles in fascicles, geometric calculation of leaf area has been shown to be accurate (e.g. Strong and Zavitkovski, 1978).

Moir and Francis (1972) examined the effects of stand density on foliage characteristics of lodgepole pine. Foliage biomass and surface area were strongly governed by stand and site characteristics, especially dominance, crown position, and fascicle age. Gary (1976) reported that needle and branchwood weight in 298 lodgepole pine trees was best estimated by logarithmic transformations of diameters at breast height. Estimated LAI was about 8 m^2 m^{-2} for a stand the same age as that reported by Moir and Francis (1972).

Table 4.—Ratios of projected leaf area to sapwood cross-sectional area for selected conifers (from Waring *et al.*, 1982).

Species	Leaf area: sapwood area, m^2 cm^{-2}
Abies amabilis (Dougl.) Forbes	0.64
Abies grandis Lindl.	0.48
Abies lasiocarpa (Hook.) Nutt.	0.75
Abies procera Rehd.	0.27
Juniperus occidentalis Hook.	0.18
Picea engelmannii (Parry) Engelm.	0.35, 0.29
Picea sitchensis (Bong.) Carr.	0.45
Pinus contorta Engelm.	0.15, 0.18, 0.17
Pinus nigra var. *maritima* (Ait.) Melv.	0.15
Pinus ponderosa Dougl.	0.25
Pinus sylvestris L.	0.14
Pseudotsuga menziesii (Mirb.) Franco	0.54
Tsuga heterophylla (Raf.) Sarg.	0.46
Tsuga mertensiana (Bong.) Sarg.	0.16

A summary of leaf area attributes of lodgepole pine appears as Table 5.

STOMATA AND WATER RELATIONS

Stomatal Behavior

Because stomata control exchange of CO_2 and water vapor, stomatal behavior and associated water relations govern the productivity of many western species (Bassman and Black, 1984). Stomatal behavior of lodgepole pine sets it somewhat apart from many of its associates.

Table 5.—Leaf area attributes of lodgepole pine.

			SOURCE
Maximum LAI:	14.0	$m^2 m^{-1}$	(Moir and Francis, 1972)
Leaf Area: Leaf Dry Weight	7.0-15.0	$m^2\ kg^{-1}$	(Moir and Francis, 1972)
Leaf Area: Sapwood Area			
Projected Leaf Area:	0.15-0.17	$m^2\ cm^{-2}$	(Kaufmann and Troendle, 1981; Waring *et al.*, 1982)
Total Leaf Area:	0.37-0.42	$m^2\ cm^{-2}$	(Kaufmann and Troendle, 1981; Waring *et al.*, 1982)

Effects of Light

With many conifers (Hinkley *et al.*, 1978), leaf conductance (k_l) increases with increased light intensity up to about 10% full sun (70-80 W m^{-2}), after which it remains constant, other factors being equal. In a greenhouse experiment with 2-year-old lodgepole pine seedlings, Dykstra (1974) showed that this conductance plateau occurred at about 50% full sun. Kaufmann (1982a, 1982b) showed that photosynthetic photon flux density (PPFD) and the absolute humidity difference from leaf to air (DAH) were the most important factors controlling stomatal function in lodgepole pine and other high elevation species. Also, k_l increased as PPFD increased from 10% full sun to full sun; the effect was most pronounced in lodgepole pine (Fig. 3).

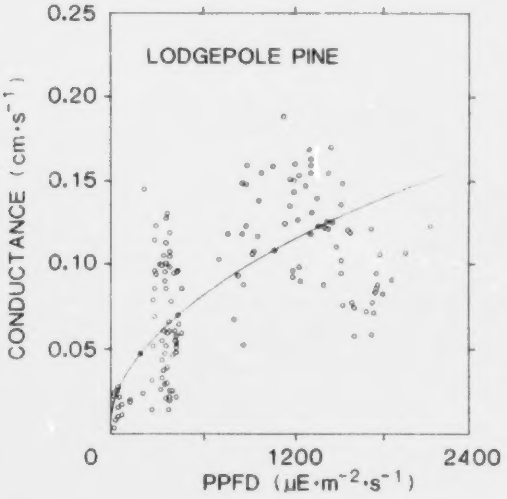

Figure 3.—Effect of light intensity on stomatal conductance in lodgepole pine (from Kaufmann, 1982a).

Stomata of some western conifers close only partially at night when evaporative demand and internal water deficits are low (Blake and Ferrell, 1977; Hinckley, 1971; Running, 1976). Lopushinsky (1975) compared stomatal apertures in the light and dark for lodgepole pine, ponderosa pine, Engelmann spruce *Picea engelmannii* Perry ex Engelm.), Douglas-fir and grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl.). Stomata of both lodgepole pine and ponderosa pine close completely in the dark and open rapidly in response to light. Lodgepole pine had the most complete stomatal closure.

Effects of Temperature

The work of Kaufmann (1976, 1982a) and Running (1976) suggests that temperature is generally not a major factor controlling leaf conductance in lodgepole pine except through its effect on leaf responses to atmospheric moisture.

Effects of Atmospheric Moisture

Differences between absolute humidities inside the leaf and the outside atmosphere (DAH) account for much of the stomatal regulation in lodgepole pine (Kaufmann, 1982a; Running, 1980a) as well as other western conifers (Running, 1976; Tan *et al.*, 1977). Kaufmann (1982a) showed the shape of the response curve of conductance vs. DAH to vary with light intensity in lodgepole pine, Engelmann spruce, subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) and aspen (*Populus tremuloides* Michx.). Needle age affects stomatal behavior in some conifers but not in others. In Douglas-fir, conductance decreases with increased leaf age but ponderosa pine shows no differences between age classes of needles (Running, 1976). Lodgepole pine shows more erratic stomatal response as needles age. Older needles tended to have lower conductances, but under conditions of water stress or low light, stomatal closure was less complete than with younger needles (Running, 1980a). Species differences can be substantial; at one high elevation site lodgepole pine had about twice the conductance of Engelmann spruce and subalpine fir at all levels of atmospheric moisture (Kaufmann, 1982a).

Atmospheric humidity and xylem sap potential interact to control k_l. Many western conifers have a threshold xylem pressure potential which causes abrupt midday stomatal closure (Hinckley *et al.*, 1978; Puritch, 1973; Seymour *et al.*, 1982; Tan *et al.*, 1977). Lopushinsky (1969) demonstrated that stomata of lodgepole pine close at much higher (less negative) ψ_s than ponderosa pine, Engelmann spruce, Douglas-fir, and grand fir (Table 6). He suggested this was evidence for more sensitive stomatal control in lodgepole pine.

Table 6. – Plant moisture stress at stomatal closure for five conifer seedlings (from Lopushinsky, 1969).

Species	Xylem Pressure Potential (MPa)
Ponderosa pine	−1.65
Lodgepole pine	−1.46
Grand fir	−2.51
Douglas-fir	−1.90
Engelmann spruce	−1.60

Threshold values for stomatal closure in lodgepole pine of −1.7 to −2.0 MPa were reported by Fetcher (1976) and Running (1980a) respectively. When midday water stress fails to reach the threshold, k_l is directly correlated to predawn (or base) leaf water potentials (Running, 1976, 1980a). Low atmospheric humidities significantly decrease midday k_l (Running, 1980a).

Effects of Cold Temperature

Overnight frost or cold temperatures depress k_l on subsequent days. Fahey (1979) monitored late winter conductance in a 100-year-old even aged stand of lodgepole pine near Albany, Wyoming (2900 m elevation). Leaf conductance was highly correlated with mean temperature of previous subfreezing nights. Base pressure potentials were also influenced by overnight freezing but were not correlated with k_l, suggesting a direct effect of cold temperatures on stomatal physiology. Running (1980a) reported a similar effect; morning leaf conductance at 10°C. was less than one-half of expected values after −3 to −4°C nights.

Additional research confirms the sensitivity of lodgepole pine to cold temperatures. Cowling and Kedrowski (1980) examined winter desiccation in white spruce, ponderosa pine, and lodgepole pine near Fairbanks, Alaska. The spruce showed ψ_l of −1.0 to −4.0 MPa and relative water contents (RWC) of 88-99%. Both lodgepole and ponderosa pine kept stomates closed all winter with ψ_l of 0.0 MPa and RWC's of 100%. Fahey (1979) reported that late winter (March-April) base ψ_s of lodgepole pine in Wyoming were usually lower than −1.3 MPa, suggesting considerable water stress. Soils were dry, with less than 7% moisture content.

Other Water Flux Components

Xylem Pressure Potential

Baldwin and Barney (1976) evaluated ψ_l during establishment of lodgepole pine and ponderosa pine seedlings near Fort Collins, Colorado. Species, seed source, year of planting, and shoot/root ratios all accounted for significant differences in ψ_l. In contrast to results reported by Running (1980a), seasonal trends in ψ_l were lacking. Leaf water potential varied by aspect, north aspects having higher potentials than south aspects.

Ritchie and Hinckley (1971) found that xylem pressure potential was up to 0.4 MPa more negative in stems than in leaves of Douglas-fir, Pacific silver fir (*Abies amabilis* Doug. ex Forbes), and noble fir (*Abies procera* Rehd.) but not in lodgepole pine or Jeffery pine (*Pinus jefferyi* Grev. & Balf.). This phenomenon was attributed to storage of water in non-conducting xylem in Douglas-fir and the true firs. Kaufmann and Thor (1982) showed that ψ_l in current and 1-year-old needles of lodgepole pine were slightly lower than those of older needles.

Soil Water

Transpiration rates of two-year-old seedlings of lodgepole pine, ponderosa pine, Douglas-fir, grand fir, and Engelmann spruce began to decline at soil water potentials (ψ_{soil}) of −0.1 to −0.2 MPa (Lopushinsky and Klock, 1974). The degree of reduction varied considerably by species (Table 7). Stomata of the pine were apparently more sensitive to increased soil moisture stress, closing at higher ψ_l. Similar results were reported by Baer (1976).

Table 7. – Reduction in transpiration of five conifer species with respect to decreased soilwater potential (from Lopushinsky and Klock, 1974).

	Transpiration (% of maximum)		
Species	−0.5 MPa	−1.0 MPa	−2.0 MPa
Ponderosa pine	38	12	25
Lodgepole pine	48	12	2
Engelmann spruce	55	25	5
Douglas-fir	59	37	17
Grand fir	63	37	17

Root Resistance

Running (1980c) used a root excision technique to estimate the proportion of total resistance (R) to water flux contributed by soil, the root, and xylem of lodgepole pine. Under both high and low flux conditions, soil and root resistance contributed greater than one-half of the total resistance in the soil-plant-atmosphere continuum (SPAC). Data suggested that R_{SPAC} was almost entirely caused by decreasing base ψ_l resulting from soil water depletion. Base ψ_l before root excision were highly correlated with total soil-plant resistance ($r^2 = .89$) and calculated root water uptake ($r^2 = .92$).

The effects of low temperature in the root zone on water uptake were examined by Running and Reid (1980). As root temperatures dropped from 22 to 0°C, ψ_l dropped. The slope of the $\Delta\psi_l$/TFD (TFD = transpiration flux density) became more negative as root temperatures decreased. Transpiration rates did not decline significantly until root temperatures dropped below 10°C. Root resistance was calculated to be 67% of total plant resistance at 7°C and 93% at 0°C.

Aerodynamic Resistance

Smith (1980) investigated the quantitative importance of aerodynamic (boundary layer) resistance to water vapor and CO_2 exchange in young lodgepole pine, subalpine fir, and juniper (*Juniperus communis* L.) growing in the Medicine Bow Mountains of Wyoming. Combinations of low stomatal resistance ($r_s < 300$ s m^{-1}) and low wind speeds (<30 cm s^{-1}) led to substantial contributions of aerodynamic resistance to water use efficiency (WUE = photosynthesis/transpiration) in all three species. These conditions occurred consistently during the morning. When aerodynamic resistances were taken into account, transpiration was calculated to be 30 to 44% less, and photosynthesis 11 to 17% less, leading to increases in WUE of from 34 to 57% (Table 8).

Table 8.—Impact of aerodynamic resistance on transpiration and photosynthesis rates (modified from Smith, 1980). Values represent changes from rates calculated when aerodynamic resistance is considered negligible.

	Transpiration %	Photosynthesis %	WUE %
Abies lasiocarpa	−44	−17	+57
Pinus contorta	−40	−11	+48
Juniperus communis	−30	−12	+34

Wind is reported to affect growth of many species through its impact on water stress. Rees and Grace (1981), however, evaluated the effects of wind and shaking on the water relations of lodgepole pine and found at both low and high wind speeds there was no effect on cuticular conductance, transpiration rates, needle conductances, total and solute pressure potentials, nor any other parameter associated with pressure-volume curves. Previous studies by the same authors (Rees and Grace, 1980a, b) showed that wind and shaking caused a reduction in extension growth of needles and shoots and reduced rates of cell division; effects apparently not caused by water stress.

Plant Capacitance

Sapwood storage water acts as a major reservoir for transpiration in lodgepole pine (Running, 1980b) and some other conifers (Waring and Running, 1978). Running (1980b) estimated available stored water could provide about 10 h of maximum and 60-80 h of minimum transpiration if all storage started at capacity and if the water could be extracted that quickly. Available water could provide transpiration for about 0.6 h maximum and 4.7 h minimum transpiration rates using 5% per day and 50% per day as conservative estimates of sapwood and leaf water exchange rates.

Needles contributed only about 4% of total storage but controlled k_l through ψ_l (Running, 1980b). Apparently, needles always get water at the expense of sapwood storage. Diurnal hysterisis loops of ψ_l vs. transpiration are found in lodgepole pine and are probably caused by a temporary depletion of the leaf water reservoir which is refilled each night from the sapwood and root uptake (Running, 1980b). Seasonally, after stem relative water contents (RWC's) are depleted to the 60-70% range, stem storage acts primarily as a temporary diurnal reservoir for refilling leaf storage. Overnight recharge of leaves from the stem allows higher transpiration rates than possible if root water supplied leaves directly.

Transpiration

Amount of Water Used

Owston *et al.* (1972) used ^{32}P to monitor water movement in 60-year-old lodgepole pine in the Sierra Nevada mountains of California. Daytime rates during summer ranged from 12 to 84 cm h^{-1}, but no movement occurred in lodgepole pine in the winter. Volume of daytime movement in individual trees in October ranged from 1.3 to 5.3 l h^{-1}.

Using the heat pulse velocity method, Swanson (1975) reported annual lodgepole pine transpiration rates of 200-400 mm depending on stand density and soil moisture. Transpiration from a thinned lodgepole pine stand in Alberta was an estimated 170 mm $year^{-1}$ compared to 239 mm in an unthinned stand. Transpiration by individual trees varied from 2 l day^{-1} during September in Alberta to 91 l day^{-1} during February in New Zealand. Average clear day use by individual trees: Colorado, 22.7 l; Alberta, 8.8 l; and New Zealand, 44.4 l.

Whole-tree potometers were used to estimate transpiration in two contrasting 100-year-old lodgepole pine stands in southeast Wyoming (Knight *et al.*, 1981). The first stand had nearly 7 times more trees and 29% less biomass though both stands had nearly identical leaf area indices (7.3 and 7.1 m^2 m^{-2}) and clear day transpiration rates (3.3 and 3.4 mm day^{-1}). Individual tree basal area and 24 h uptake were highly correlated. The largest trees (20-26 cm dbh) transpired 40-44 l on a clear day in summer in agreement with values reported by Swanson (1975). Maximum hourly uptake for larger trees was 2.5 to 3.5 l with overnight uptake about 12% of the 24 h uptake. Overcast days reduced potometer uptake by 30-44% and during rainy periods, uptake was near 0.

Running *et al.* (1975) presented a water flux model for lodgepole pine. Changes in rooting volume, amount of sapwood, leaf area, and leaf conductance are taken into account. The model also constrains water uptake and transpiration due to cold soil and air temperatures.

Species Comparisons

Transpiration rates in lodgepole pine have been compared to several of its associates. In an early study, Roeser (1932) found that over a temperature range from 16 to 51°C, lodgepole pine had higher rates of transpiration per gram dry weight of seedling than ponderosa pine, Douglas-fir, and Engelmann spruce. Gail and Long (1935) reported that transpiration rates in ponderosa pine were greater than in lodgepole pine in both still air (12.31 vs. 6.71 g dm^{-2}) and in wind (14.63 vs. 11.74 g dm^{-2}). Wind increased transpiration rates in lodgepole pine by 74.98% but in ponderosa pine by only 18.85%.

Water relations of lodgepole pine, Engelmann spruce, and subalpine fir were monitored in open and understory sites during the summer in southeastern Wyoming by Knapp and Smith (1981). Maximum k_l at the open site was greatest for subalpine fir (6.1 mm s^{-1}) followed by lodgepole pine (3.9 mm s^{-1}) and Engelmann spruce (1.5 mm s^{-1}). Values for all three species were lower at the understory site but lodgepole pine showed the greatest reduction (64%) compared to subalpine fir (39%) and spruce (13%). Minimum ψ_s were usually greater in lodgepole pine (−1.55 MPa) compared to subalpine fir (−1.9 MPa) and Engelmann spruce (−2.0 MPa). Reductions in DAH (humid vs. dry day) increased k_l in Engelmann spruce by 230%, lodgepole pine by 115%, and subalpine fir by only 50%. Maximum TFD's were: subalpine fir, 83 mg m^2 s^{-1}; lodgepole pine, 73 mg m^2 s^{-1}; and spruce, 30 mg m^2 s^{-1}. Additional comparisons of water relations in lodgepole pine and other western conifers can be found in Cowling and Kedrowski (1980), Kaufmann (1982a, b), Lopushinsky (1969, 1975), Owston *et al.* (1972), Ritchie and Hinckley (1971), Running (1976), Smith (1980), and Wambolt (1973).

Genetic Variation

There is considerable genetic variation in response to water stress in lodgepole pine. Dykstra (1974) monitored drought resistance during and following moisture stress in 2-year-old seedlings from diverse provenances. Results showed considerable variation by provenance. Perry *et al.* (1978) evaluated 16 wind pollinated families representing 6 populations of lodgepole pine. Various levels of osmotic stress were imposed using PEG 6000. Families varied substantially in stress resistance but populations did not.

Effects of Stand Density on Water Use

Thinning experiments in 47-year-old lodgepole pine stands near Bend, Oregon, suggest soil moisture withdrawal is less after thinning than before (Dahms, 1971, 1973). In contrast, Knight *et al.* (1981) found that in two lodgepole pine stands of different densities, clear day transpiration rates were nearly identical. Wambolt (1973) examined 21 stands consisting of 7 different species (including lodgepole pine) in western Wyoming and found a high correlation (r^2 nearly 1.0) between stand density and ψ_s suggesting intraspecific competition for available moisture.

Summary Water Use Attributes

A summary of stomatal and water use attributes for lodgepole pine appears as Table 9.

BIOMASS PRODUCTION

A measure of productivity in a species is its ability to convert photosynthetic products into biomass. From a crop production standpoint, we are interested in how those photosynthates are partitioned throughout the plant. The way in which this partitioning occurs has a major influence on quality of the crop as well as quantity. Biomass distribution in stands and

Table 9.—Stomatal and water use attributes of lodgepole pine.

		SOURCE
Maximum Leaf Conductance:	0.40 s cm^{-1}	(Korner *et al.*, 1979)
ψ_l for Stomatal Closure:	−1.46 to −2.00 MPa	(Fetcher, 1976; Lopushinsky, 1969; Running, 1980a)
Transpiration Maximum:	40-44 L d^{-1}	(Knight, *et al.*, 1981; Swanson, 1975)
	(91 L d^{-1} N.Z.)	(Swanson, 1975)
Water Movement:	12-84 cm h^{-1}	(Owston *et al.*, 1972)
Transpiration Flux Density:	0.55-3.20 μg cm^{-2} s^{-1}	(Running, 1980a, 1980b)
	(7.3 μg cm^{-2} s^{-1})	(Knapp and Smith, 1981)

individual trees of lodgepole pine has been reported in several studies. Many of these (Chapman *et al.*, 1984; Gholz *et al.*, 1979; Singh, 1982, 1984; Stanek and State, 1978) have focused on development of equations for predicting biomass based on simple measurements. Other studies have concentrated on distribution in the crown (Brown, 1978; Gary, 1976; Hanson, 1975; Moeur, 1981; Moir and Francis, 1972; Storey *et al.*, 1955) or aboveground biomass (Weaver and Forcella, 1977). Two studies report on both above- and below-ground biomass distributions in lodgepole pine (Pearson *et al.*, 1984; Johnstone, 1970).

Gary (1978) investigated the vertical distribution of needles and branchwood in thinned and unthinned 80-year-old lodgepole pine. Compared to the thinned stand, weight distribution of needles and branchwood in the unthinned stand was strongly skewed upward in the top half of the canopy. In six contrasting lodgepole pine stands of similar age (≥ 75 years old) in southeastern Wyoming (Pearson *et al.*, 1984), total biomass ranged from 123 to 180 Mg ha^{-1}. Root:shoot ratios in two very dense stands (14,640 and 9,700 trees ha^{-1}) were much higher than in four open stands (ca. 0.5 vs. 0.28). Biomass partitioning was as follows: boles, 61%; branches, 7%; foliage, 6%; woody roots, 20%; and fine roots, 6%.

Growth analysis techniques were used by van den Driessche and Wareing (1966) to compare dry matter production in first year seedlings of lodgepole pine, Monterey pine, Austrian pine and Scot's pine. There were no differences in relative growth rate (RGR) between species except between Monterey pine and Austrian pine. At high levels of mineral nutrition, Monterey pine had higher RGR's than Austrian pine though the reverse was true at low nutrient levels. Also, there were no differences in net assimilation rate (NAR) between species but NAR appeared to increase and decrease with nutrient supply. Sweet and Wareing (1968) found that leaf weight ratios (LWR = leaf weight/plant weight) differed significantly between four provenances of lodgepole pine. Observed differences in RGR's could be accounted for by difference in LWR and PS.

A more complete treatment of biomass characteristics of lodgepole pine can be found in the paper by Chapman (1984) reported elsewhere in this volume.

ROOT RELATIONS

The study of root systems in lodgepole pine, as in many other species, remains an enigma; especially for large, forest grown trees. Recent research efforts are beginning to explore physiological and morphological characteristics of roots in lodgepole pine (e.g., Pearson *et al.*, 1984).

Flooding Tolerance

Compared to many northwestern tree species, lodgepole pine is tolerant to flooding. In laboratory comparisons of lodgepole pine, Douglas-fir, Sitka spruce, western hemlock, western redcedar (*Thuja plicata* Donn ex D. Don), and red alder (*Alnus rubra* Bong.), winter flooding for 1 to 4 weeks had little effect on any species except Douglas-fir. Summer flooding for 4 to 8 weeks affected all six species but lodgepole pine and western redcedar were most tolerant to the treatment. Lodgepole pine, western redcedar, red alder and Sitka spruce are all tolerant of shallow water tables, though lodgepole pine, western redcedar, and western white pine (*Pinus monticola* Doug. ex D. Don) all grow best over deeper water tables (Minore, 1970).

The work of Coutts and Philipson (1978a, b) and Philipson and Coutts (1978, 1980) help to explain the tolerance of lodgepole pine to flooding. Rooted tip cuttings of both lodgepole pine and Sitka spruce were grown under controlled conditions and subjected to flooding while active or dormant and at 6 and 15°C (Coutts and Philipson, 1978a). Actively growing tips were more susceptible to waterlogging than the region behind the tip. Actively growing roots of the pine were more tolerant to waterlogging than the spruce. Both species were tolerant to flooding when dormant. Lodgepole pine roots were able to grow 20 cm below the water table at 10°C whereas penetration by spruce roots was minimal (Coutts and Philipson, 1978b). Pine root penetration into waterlogged soil was greater at 10°C than 20°C and root tip survival was higher if the roots were acclimated before severe flooding. The flood tolerance of lodgepole pine apparently results from production of large, gas-filled cavities in inundated roots (Coutts and Philipson, 1978b) and the ability to actively transport oxygen to submerged tips in these cavities (Philipson and Coutts, 1978, 1980). Regions of 0_2 entry are the needles and lenticels on woody roots. In experiments where the root systems of individual plants were split between flooded and non-flooded pots, a reduction in growth of woody roots and increased production of lenticels was noted on the flooded portion (Coutts, 1982).

Mineral Nutrition

Etter (1969) evaluated the effects of different nutrient regimes on drought resistance in lodgepole pine. Increased nitrate-nitrogen supply (from 0.4 to 8.0 meq l^{-1}) reduced root/leaf weight ratios and soluble carbohydrate and starch contents in both leaves and roots. Drought survival was lowest in seedlings grown at the highest nitrate level. Several reports (Bigg and Daniel, 1978; Krajina *et al.*, 1973) indicate that the ammonium form of nitrogen is preferred over nitrate-nitrogen in lodgepole pine.

Initial nutritional differences in the rooting environment do not lead to dominance by certain roots (Coutts and Philipson, 1977). In solution culture tests, individual root systems of lodgepole pine were divided between high (near optimal) and low (deficient) nutrient regimes (Coutts and Philipson, 1977). The low regime inhibited root growth whereas the high regime stimulated it. When slower growing roots from the low nutrient regime were transferred to the high regime, renewed and more rapid growth occurred compared to roots remaining in the low regime (Fig. 4).

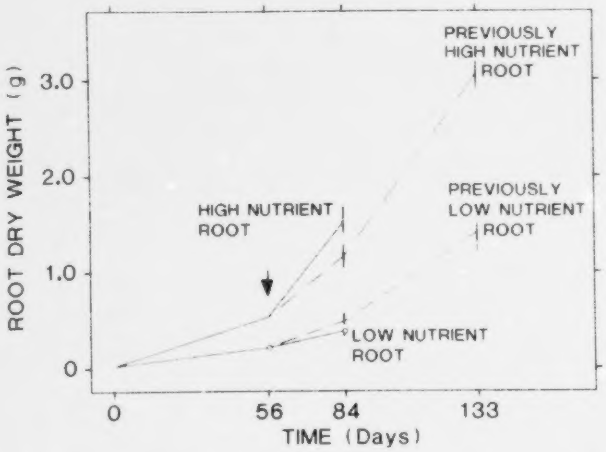

Figure 4.—Time course of dry matter accumulation in *Pinus contorta* roots. The plants had divided roots growing in either an uneven (—) nutrient regime of high (●) and low (o) nutrient concentrations, or in uniform high (---) nutrient conditions. Certain plants were transferred from the uneven to the uniform regime at 56 days (arrowed). The vertical line on one side of a point shows the standard error (from Coutts and Philipson, 1977).

Root Exudations

Lopushinsky (1980) observed root pressure exudation from detopped seedlings of lodgepole pine and seven other northwest conifers. Exudation was not dependent on the presence of new root growth since exudation occurred from plants with completely suberized root systems as well. The exudate was dilute (osmotic potentials −0.24 to −0.78) and consisted of a variety of sugars, amino acids, and other organic acids and nitrogenous compounds (Ketchie and Lopushinsky, 1981).

The effects of water stress on exudation from roots of intact lodgepole pine seedlings was reported by Reid and Mexal (1977). PEG 4000 was used as an osmoticum to develop water potentials of −0.2 or −0.4 MPa in a 7-year-old plant. Roots subjected to −0.4 MPa exuded the most ^{14}C-labeled photoassimilates but more material was also translocated to these roots. Some roots exuded greater than 80% of ^{14}C activity translocated to them over a 10-day period. Exudation did not appear to be affected by mycorrhizal infection.

COLD HARDINESS

Very young lodgepole pine seedlings (22-days-old) are reported to better withstand a single exposure to night temps of −8°C than older (36-day-old) seedlings (Cochran and Bernsten, 1973). Preconditioning at temperatures slightly above freezing reduced mortality when seedlings are subsequently exposed to minimums of −7°C or less (Cochran and Bernsten, 1973). Photoperiod appears to be the major stimulus for cold hardening (Cochran and Bernsten, 1973; Jonsson *et al.*, 1981) but low night temperatures are primarily responsible for its development (Jonsson *et al.*, 1981). In Alaska (Kedrowski, 1980), dehardening of lodgepole pine in the spring begins only after mean temperatures rise above 0°C. Large decreases in needle phospholipids occur during the dehardening process but do not necessarily coincide with hardiness losses. Changes in phospholipids appear to be initiated by changes in day length (Kedrowski, 1980).

There is considerable genetic variation in cold hardiness between populations of lodgepole pine (Jonsson *et al.*, 1981; Rehfeldt, 1980). Latitude, elevation, and geographic origin of the seed accounted for most of this variation. Jonsson *et al.* (1981) found strong correlations at the population level between frost damage and a) lengthening of secondary needles, b) dry matter content of apical or lateral shoots (upper 3 cm), and c) anthocyanin color.

AIR POLLUTION RESPONSES

Lodgepole pine grows naturally or has been planted in areas susceptible to anthropogenic emissions, both in the United States and in Europe. As a result, some effort has been undertaken to understand physiological and morphological responses of this and other species to air pollution.

Sulfur Dioxide

Sulfur dioxide is a major source of air pollution in many industrialized areas. The susceptibility of lodgepole pine to this gas varies by seed source and the type of exposure. Lang *et al.* (1971) found that coastal provenances (Washington and Oregon) were more susceptible to SO_2 damage than interior ones (Idaho and Wyoming). The degree of sensitivity depends on whether the exposure was acute or chronic. Garsed and Rutter (1982) compared SO_2 sensitivity of three populations of lodgepole pine (2 var. *latifolia*, 1 var. *contorta*), Sitka spruce, Norway spruce (*Picea abies* [L.] Karst.), Scots pine, and Austrian pine. With long-term, low concentrations ($>$9 months at 200 μg m^{-3} SO_2), Scots pine and Austrian pine showed no significant effects whereas lodgepole pine and the spruces were sensitive. At acute levels (6 h at 8000 μg m^{-3} SO_2), Scots pine and Austrian pine were most severely affected, the spruces least. Lodgepole pine was intermediate in sensitivity (Table 10).

Sulfur dioxide in either gaseous (Legge *et al.*, 1977) or aqueous form (Malhorta, 1977) reduces PS rates in lodgepole pine. Aqueous SO_2 causes a disruption in the structural integrity of chloroplasts which is more pronounced in older, less metabolically active tissue (Malhorta, 1976). Chlorophyll breakdown also occurs and it appears that chlorophyll a is more sensitive to SO_2 than chlorophyll b (Malhorta, 1977). Other biochemical effects of SO_2 in lodgepole pine include inhibition of lipid biosynthesis (Malhorta and Khan, 1978) and reductions in needle ATP contents (Harvey and Legge, 1979).

Table 10. – Relative sensitivity of conifer populations to acute SO_2 injury. Most sensitive = 8; most resistant = 1 (from Garsed and Rutter, 1982).

Pinus sylvestris	7.4
Pinus nigra	6.6
Pinus contorta "Clearwater"	5.0
Pinus contorta "Terrace"	5.5
Pinus contorta "Long Beach"	4.1
Picea abies	1.3
Picea sitchensis "Forks"	0.6
Picea sitchensis "East Graham Island"	0.8

Fluoride

Gaseous fluorides are emitted as a by-product of aluminum manufacturing in the northwest United States. Carlson (1978) and Carlson *et al.* (1979) investigated the impact of F_2 emissions in northwest Montana on foliar symptoms and radial growth of lodgepole pine, Douglas-fir, and western white pine. Both mottle and tip necrosis of needles increased in direct proportion to increasing fluoride levels. Current 10-year periodic annual radial growth decreased significantly in response to increased foliar fluoride levels. Significant adverse effects occur at concentrations as low as 8-10 ppm.

RESISTANCE TO INSECT ATTACK

The most extant insect problem of lodgepole pine is attack by the mountain pine beetle (MPB). Hanover (1975a) suggested monoterpenes as an endogenous insect repellent in conifers and identified a genetic hierarchal regulation of terpene fractions in lodgepole pine (Hanover, 1975b). However, Hanover and Furniss (1966) could find no consistent differences in Douglas-fir resistant to attack by Douglas-fir bark beetle in attacked and unattacked trees. Several studies have attempted to relate monoterpene content of lodgepole pine with attack by the MPB. Smith (1983) recently completed a regional study of monoterpene content in lodgepole pine. Cole *et al.* (1981) found that high concentrations of monoterpenes coincided with larger diameter trees, the expected region of high mountain pine beetle survival.

Raffa and Berryman (1982) attempted to identify physiological differences between lodgepole pines resistant and susceptible to attack by MPB. No relationship could be established between resistance and daily rate of resin flow, rate of resin crystallization, monoterpene content, monoterpene composition, or current growth rate. Secondary wound response to attack by fungi vectored by MPB was the most important defense mechanism and did involve increased flow of resin. Reid (1961) evaluated moisture changes in lodgepole pine before and after attack by MPB. Moisture content of the outer sapwood of non-infested trees ranged from 85-165% of oven dry weight but was as low as 16% in trees infested for one year. Non-infested trees show diurnal and seasonal changes in sapwood moisture content whereas infested trees do not.

Partial girdling of lodgepole pine seedlings, done to simulate attacks by the weevil *Hylobius warreni*, reduced leader elongation and radial growth of both leader and lateral roots (Cerezke, 1974). Defoliation in 2-0 seedlings of lodgepole pine reduced new root initiation (Carlson, 1977).

Effects of dwarf mistletoe (*Arceuthobium americanum* Nutt. ex Engelm.) on lodgepole pine physiology have been studied by Rediske and Shea (1961) and Mark and Reid (1971). Dwarf mistletoe photosynthesizes and translocates much of that product into the pine host (Rediske and Shea, 1961). Photosynthate produced by terminal needles of lodgepole pine is intercepted and accumulated by intervening dwarf mistletoe plants before it can be translocated to the pine root system (Rediske and Shea, 1961). Xylem water potentials of dwarf mistletoe shoots were more negative than the pine branches on which they were growing, creating a water potential gradient favorable to the mistletoe, even when the pine is under considerable water stress (Mark and Reid, 1971).

PHYSIOLOGY OF GROWTH STAGNATION

Lodgepole pine, like several other western conifers (e.g. ponderosa pine, western hemlock) can become established at very high densities, leading to what is referred to as "stagnated" stands. With lodgepole pine the problem is particularly prevalent because of the serotinous cone habit. Many years' seed production can be stored in these cones which open under the influence of fire. Seed is released on an almost ideal seedbed, free of competing vegetation and high in recently released nutrients. Seedlings may establish in numbers approaching 1 million trees ha^{-1}.

Though competition is extreme under these conditions and some mortality occurs, densities can remain very high. For example, Brown (1975) reported a 70-year-old stand with 250,000 trees ha^{-1}. Thinning studies have shown that unless released at a very early age, stagnated growth persists after density reductions (Cole, 1975). This suggests that there are certain physiological adaptations that allow persistence of stagnated growth.

Photosynthesis, leaf area, water relations, and biomass partitioning in lodgepole pine stands were studied by Bassman (1982) to characterize stagnated growth in physiological terms. To date, only leaf area and biomass data have been reported (Roydhouse *et al.*, 1984; Bassman and Crane, 1984). Four density classes were selected in a 20-year-old stand near Williams Lake, B.C., to provide comparisons between unstagnated (5000, 20,000 trees ha^{-1}), trees near stagnation (50,000 trees ha^{-1}), and stagnated trees (100,000 trees ha^{-1}). Height and live crown ratio data suggest stagnation occurs between 20,000 and 50,000 trees ha^{-1}. Basal area was maximum at 50,000 trees ha^{-1} (Table 11). Maximum per hectare biomass occurred at 50,000 trees ha^{-1} whereas maximum per tree biomass occurred at 5000 trees ha^{-1}. Except for the 5000 tree ha^{-1} class, the ratio of biomass component to mean tree weight was fairly constant. The main stem contributed ca. 70%, branches 10%, and leaves 20% of total tree biomass. In the 5000 trees ha^{-1} class, branches contributed nearly 30% and the main stem contributed 50%.

Maximum leaf area index (LAI occurred in the 50,000 trees ha^{-1} class but maximum per-tree leaf area occurred in the 5000 class. The proportion of total plant leaf area represented by each of three age classes of needles was fairly constant across density classes. The ratio of bole surface area to leaf area (BSA/LA = a measure of non-photosynthetic to photosynthetic tissue) increased with increasing density, nearly doubling at the highest density.

The possibility that stagnated growth was a periphytic effect was tested by Worrall *et al.* (1984). If this were so, vigorous scions grafted onto suppressed trees would grow relatively fast and stagnant scions would continue to grow slowly. Instead, reciprocal grafts of vigorous and stagnant scions on the two types of rootstock showed growth to assume that typical of the rootstock by the third season after grafting.

SUMMARY

This paper has reviewed literature pertaining to the vegetative physiology of lodgepole pine. Photosynthesis in lodgepole pine is typical of western conifers and C_3 plants in general but light saturation occurs at higher levels than in other species. Leaf area production adheres to pipe model theory being closely related to sapwood area.

Stomatal behavior and water relations are well studied in lodgepole pine. Light intensity and the absolute humidity difference from leaf to air are the most important factors controlling leaf conductance. Lodgepole pine has a threshold xylem pressure potential which causes abrupt midday stomatal closure. When midday water stress fails to reach the threshold, leaf conductance is correlated to predawn leaf water potential. Overnight frost or cold temperatures depress leaf conductance on subsequent days. Soil and root resistance contribute over one-half of the total resistance to water movement in the soil-plant-atmosphere continuum. Water stored in the sapwood can ameliorate the effects of daily water deficits, acting as "capacitance" for water flux in lodgepole pine.

Lodgepole pine seedlings are tolerant to flooding conditions compared to several northwest tree species. Flood tolerance apparently results from production of large gas-filled cavities in the roots and the ability to actively transport oxygen in these cavities.

Photoperiod is the stimulus for cold hardening in lodgepole pine but low night temperatures are responsible for development of hardiness. Latitude, elevation, and geographic origin of seed account for considerable variation in cold hardiness of lodgepole pine.

Lodgepole pine is intermediate in tolerance to acute exposures to sulfur dioxide. Exposures to sulfur dioxide result in breakdown of chloroplasts and chlorophyll and inhibition of lipid biosynthesis. Significant adverse effects occur when lodgepole pine is exposed to even very low concentrations of gaseous fluorides.

Resistance of lodgepole pine to attack by mountain pine beetle is not directly related to monoterpene content, but increased resin flow does occur in reponse to secondary infection by the fungi vectored by mountain pine beetle. Relations between lodgepole pine and dwarf mistletoe result in water potential gradients favorable to the mistletoe. Any dwarf mistletoe between photosynthesizing shoots and roots of lodgepole pine is able to intercept photosynthates before they can be transported to the roots.

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Table 11.—Stand and tree characteristics of stagnated and unstagnated densities of lodgepole pine in central British Columbia (Bassman and Crane, 1984).

DENSITY CLASS	HEIGHT	LIVE CROWN RATIO	BASAL AREA	BIOMASS		LAI	LEAF AREA	BSA/LA
(Trees ha^{-1})	(m)	(m)	(m^2 ha^{-1})	(kg ha^{-1})	(kg tree^{-1})	(m^2 m^{-2})	(dm^2)	(m^2 m^{-2})
5,000	4.33	0.804	32.92	45,013	7.015	6.73	10.49	0.98
20,000	4.14	0.568	37.87	51,246	1.898	7.36	2.73	1.44
50,000	3.62	0.568	50.27	52,668	1.064	10.09	2.04	1.58
100,000	1.90	0.511	32.11	27,577	0.253	4.43	0.41	1.82

LIST OF ABBREVIATIONS

ATP	adenosine 5-triphosphate
CO_2	carbon dioxide
DAH	absolute humidity difference from leaf to air
E	Einstein
ft-c	foot-candle
F_2	fluorine
h	hours
k_l	leaf conductance
LAI	leaf area index
LWR	leaf weight ratio
m	meters
NAR	net assimilation rate
O_2	oxygen
Pa	Pascal
PPFD	photosynthetic photon flux density
ppm	parts per million
PS	photosynthesis
R	resistance
r_m	mesophyll resistance
r_s	stomatal resistance
s	seconds
SO_2	sulfur dioxide
TFD	transpiration flux density
W	Watts
WUE	water use efficiency
ψ_l	leaf water potential
ψ_s	shoot water potential

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GEOGRAPHIC VARIATION IN LODGEPOLE PINE AND ITS IMPLICATIONS FOR TREE IMPROVEMENT IN BRITISH COLUMBIA

Cheng C. Ying, K. Illingworth and M. Carlson

ABSTRACT

In reponse to an anticipated increase in the planting and intensive management of lodgepole pine, a comprehensive provenance program was initiated and a series of field tests were established in the interior of British Columbia in the early 1970's. These tests have been assessed periodically and the results are presented in this report.

Lodgepole pine appears to be plastic; survival was better than 90% on even extremely harsh environments. Coastal provenances, although suffering repeated winter injury, are still living.

Site and provenance variables markedly affect the growth of lodgepole pine. After ten growing seasons, mean height of individual test plantations ranged from 1.4 to 4.8 m. Mean height of provenances varied from 0.3 to 2.25 m on poor growing sites and from 1.4 to 6.3 on good sites. These large differences suggest a potential for increasing the productivity of lodgepole pine plantations by planting selected seed sources on those sites, which could repay investments in intensive silviculture.

The 140 provenances tested can be immediately subdivided into two groups based upon response to interior test environments. Those from coastal, far southern and far northern continental environments exhibit poor cold tolerance and/or reduced growth; those from Alberta and the B.C. Interior suffer less cold-related damage and grow relatively well. Only the second group is of interest in our practical breeding programs. For these sources geographic variables of elevation and latitude can be used to explain some of the variation in growth response. In general, however, predictability of performance based on elevation and latitude of seed source is low. Several low- to mid-elevation provenances appear to be broadly adapted with successful transfers from source to planting site of ±3° latitude and up to 400 m in elevation. These provenances will provide interim sources of seed for reforestation, as well as selected trees for testing across many widely separated breeding zones throughout the more productive parts of the B.C. Interior.

INTRODUCTION

Lodgepole pine is a major component of British Columbia's forest resource, occurring in both pure and mixed stands on approximately 19 million hectares of forest land, primarily in the interior of the province.

Although in 1981/82 lodgepole pine contributed more than one-third of the total volume harvested in the B.C. Interior, its rise in economic importance spans only two decades, and this rise is paralleled by a growing recognition of lodgepole pine as a valuable plantation species. Since the first trees were planted near Prince George in 1966, annual planting has increased steadily, reaching 15 million trees in 1983 (i.e , 20% of the total for the Interior), and projected to reach 73 million trees annually (41% of the Interior program) by the turn of the century.

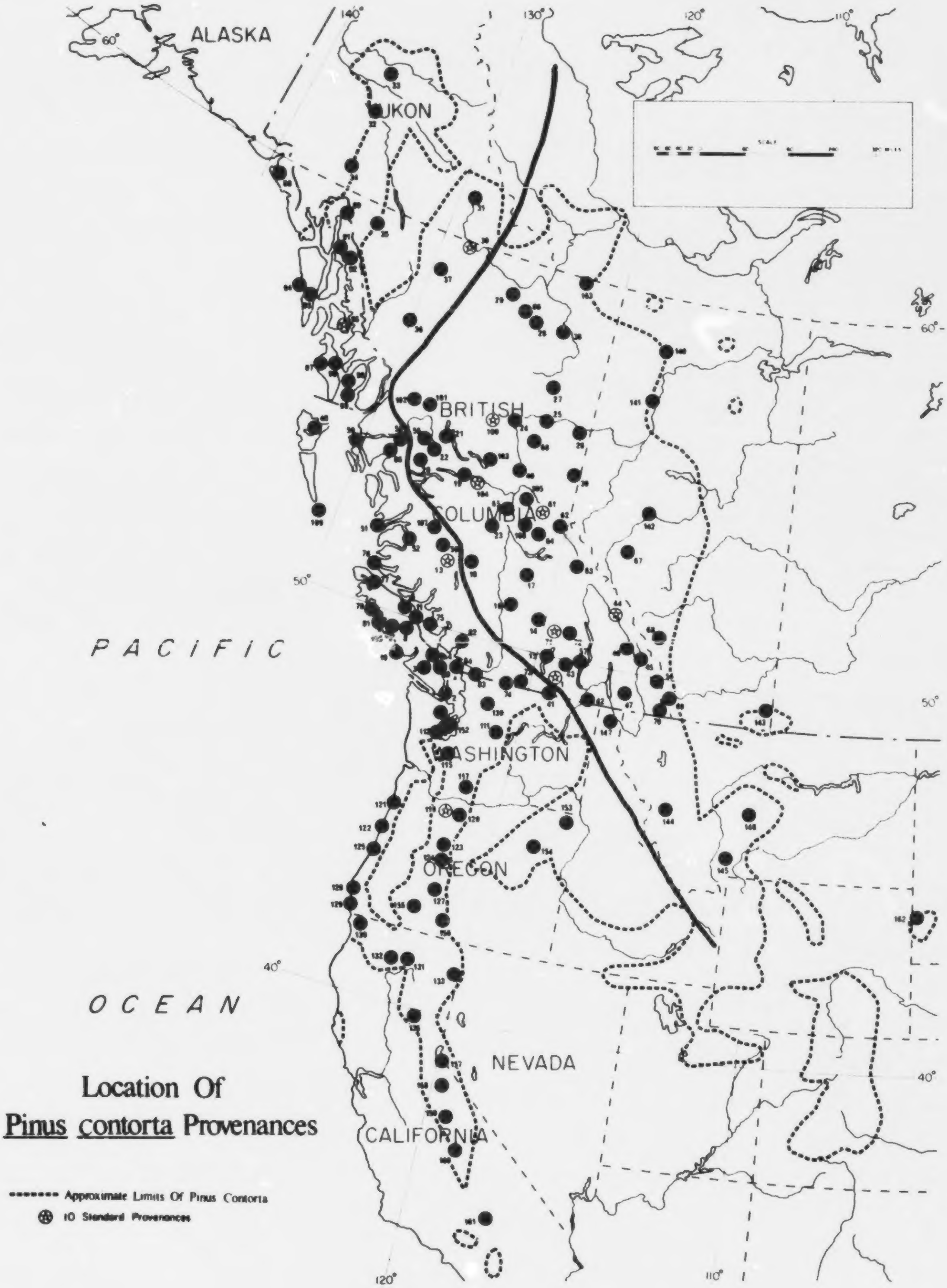
In a program of this scale, determining the range of environments across which populations can be transferred without loss of adaptability and attendant loss of productivity (i.e., the derivation of so-called "seed transfer rules") demands a knowledge of the species' genecology. In addition, a planting program of this magnitude readily justifies efforts to improve the species genetically by breeding. In anticipation of these developments, a comprehensive provenance research program was initiated in the late 1960s. It includes a network of field tests established from 1973 to 1975 throughout the B.C. Interior. This paper summarizes some results of this work, based on 10-year growth data, and comments on their implications for intensive silviculture, including genetic improvement.

The Provenance Testing Program

1. The data stem from two main projects: Range-wide provenance tests. Population samples comprising seed of 140 provenances from throughout the natural geographic range of lodgepole pine were collected, sown at Red Rock Nursery, south of Prince George, and the resulting trees were planted at 60 test locations throughout the B.C. Interior (Figs. 1 and 2; Table 1). To facilitate the location of test sites, 12 broad geoclimatic regions were delineated, primarily on the basis of latitude and moisture regime. Within each region, five test sites were selected so that major local variables, such as soil and elevation, could be sampled.

On each of the five sites within a given region, a subset of 60 provenances (of a total of 140) were tested. The 60 sources comprised 10 standards (sources tested across all regions), all provenances indigenous to the region, most provenances from adjacent regions, and certain others from the extremes of the species' range. Thus, overlapping sets of provenances were tested across the 12 regions, and in general, any given provenance was tested in 6-8 regions, i.e., at 30 to 40 sites.

All 60 sites were planted in the spring of 1974, and they were assessed after 3, 6, and 10 growing seasons.


ALASKA
60°
140°
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120°
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YUKON
BRITISH
COLUMBIA
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OCEAN
WASHINGTON
OREGON
NEVADA
CALIFORNIA
40°
40°
120°
110°
SCALE
Location Of
Pinus contorta Provenances
Approximate Limits Of Pinus Contorta
10 Standard Provenances

Fig. 1.—Location of the 140 provenances and the approximate division of the two broad geographic groups.

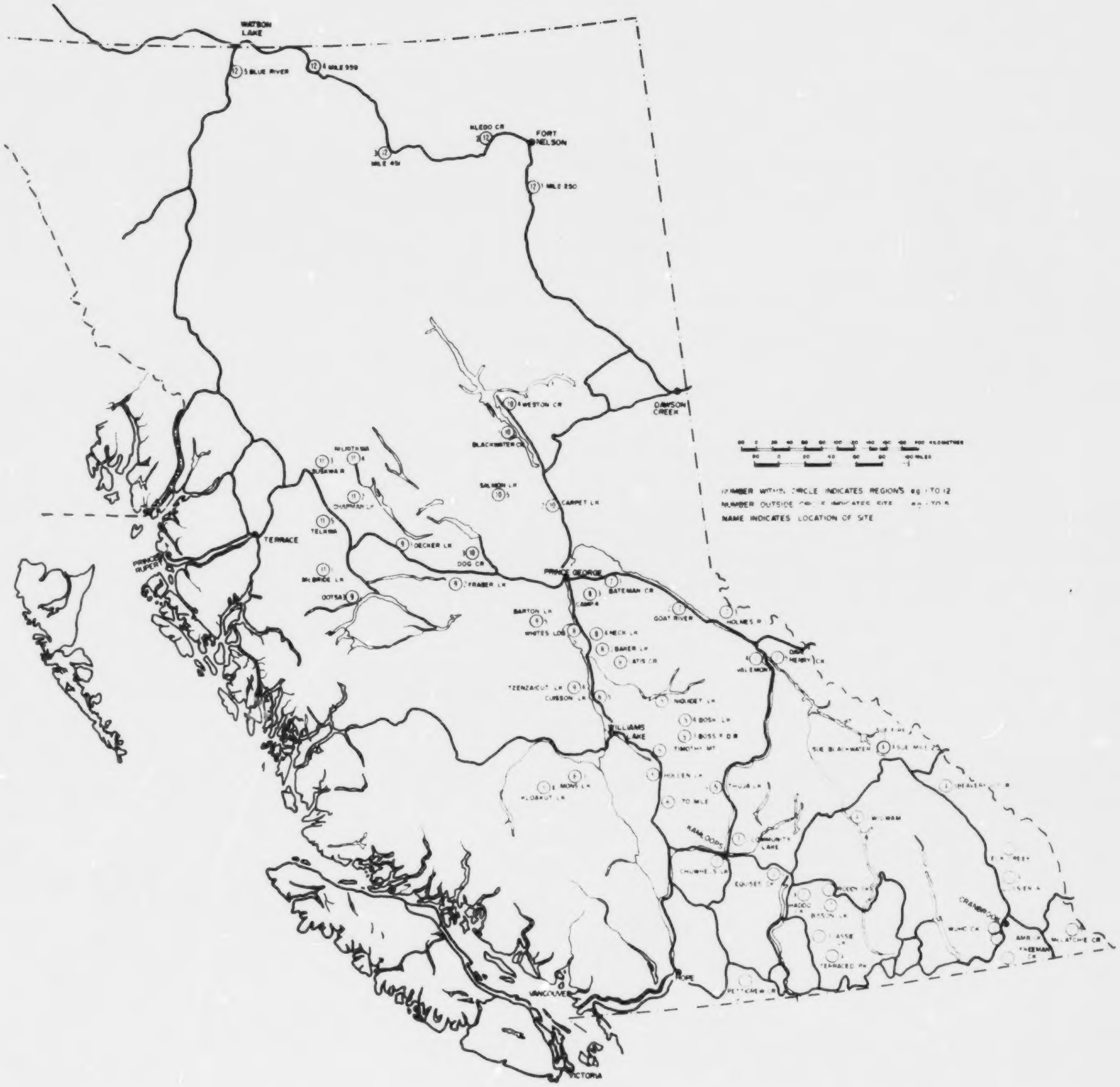
WATSON LAKE
12 5 BLUE RIVER
12 4 MILE 559
KLEDO CR
2 12
FORT NELSON
3 12
MILE 451
12 1 MILE 250
DAWSON CREEK
10 4 WESTON CR
1 10
BLACKWATER CR
SALMON LK
10 5
2 10 CARPET LK
11 3
11 4
11 2
CHAPMAN LK
11 5
TELKWA
TERRACE
PRINCE RUPERT
9 1 DECKER LK
DOG CR
FRASER LK
11
MC BRIDE LK
OOTSA
9
PRINCE GEORGE
7 1
8 3 BATEMAN CR
CAMP 4
BARTON LK
WHITES LDG
4 NECK LK
BAKER LK
ATIS CR
7
GOAT RIVER
HOLMES R
VALEMOUNT
HENRY CR
TZENZAICUT LK
CUISSON LK
NOUDET LK
4 BOSH LK
1 BOSS R D R
WILLIAMS LAKE
TIMOTHY MT
SIE BLACKWATER
SUPERIOR
MILE 25
THUJA LK
70 MILE
MONS LK
KAMLOOPS
COMMUNITY LAKE
WIGWAM
EQUISES CR
HADDO LK
BISON LK
CASSIE LK
TERRACED PK
CRANBROOK
AMP R
MCLATCHIE CR
FREEMAN CR
HOPE
VANCOUVER
VICTORIA
NUMBER WITHIN CIRCLE INDICATES REGIONS eg 1 TO 12
NUMBER OUTSIDE CIRCLE INDICATES SITE eg 1 TO 5
NAME INDICATES LOCATION OF SITE
KILOMETRES
MILES

Fig. 2.–Location of lodgepole pine provenance trials in the B.C. Interior.

Table 1.–Ten-year survival, height growth and damage assessments, by region and test site.

Region No.		Test Site Name	Elev. m	Lat.	Long.	BGCzone[1]	Survival[2] %	Height[3] %	Stem Rust[4] %	Needle Cast[5] Score	Root Weevil %	Toppling[6] %	Overall Rating[7]
1	1	WUHO CR	1340	49 27	115 57	MSa	95	366	0.9	1.5	0	L	I
1	2	LAMB CR	1250	49 19	115 54	ICHa2	94	369	0.9	0.4	2.3	L	G
1	3	ELK CR	1190	50 15	115 29	MSa	79	302	0.6	0.4	0.2	L	I
1	4	LUSSIER R	1650	49 48	115 30	ESSFa	95	221	0.4	0.2	0	L	I
1	5	FREEMAN CR	1520	49 05	115 51	ICHa2	95	372	0.7	0.0	0	L	G
2	1	RODDY CR	1460	50 05	118 34	ESSFa	94	310	0.4	0.0	0	L	I
2	2	BISSON L	1130	50 02	118 34	ICHa2	78	298	2.1	1.6	0	L	I
2	3	LASSIE L	1370	49 37	118 55	ICHc2	95	324	0.6	–	0	M	G
2	4	TERRACED PK	1830	49 23	118 46	ESSFc	91	169	0.3	0.0	0	S	P
2	5	McLATCHIE CR	1550	49 21	114 41	ESSFa	95	345	1.1	0.1	0	M	I
3	1	CHUWHELS L	1430	50 35	120 37	MSc	85	207	low	–	0	L	P
3	2	COMMUNITY L	1370	50 55	120 04	MSb1	92	321	2.0	0.0	0	L	G
3	3	PETTIGREW CR	1520	49 15	120 12	MSc	88	236	0.7	0.0	0	L	I
3	4	HADDO L	1340	50 05	119 06	MSb2	90	320	4.7	–	0	L	I
3	5	EQUISES CR	1370	50 22	119 37	MSb1	88	294	1.7	0.0	0	M	I
4	1	WIGWAM	790	50 49	117 59	ICHa2	85	368	1.2	3.2	0	M	I
4	2	SUE BLACKWATER	1550	51 34	117 24	ESSFc	97	232	1.7	0.0	0	S	P
4	3	SUE FIRE	1190	51 34	117 21	ICHa2	98	360	1.1	0.5	0	L	G
4	4	SUE MILE 25	950	51 35	117 19	ICHa2	96	403	1.4	2.3	0	L	G
4	5	BEAVERFOOT R	1370	51 02	116 20	MSa	83	228	1.1	0.0	0	L	P
5	1	NIQUIDET L	950	52 27	121 19	ICHe	90	334	5.8	severe	10.0	L	P
5	2	TIMOTHY MT	1280	51 54	120 17	SBS	90	239	2.9	0.2	0.6	L	I
5	3	BOSS FDR	1190	51 59	120 48	ESSFh	85	334	1.9	1.2	0	S	I
5	4	BOSK L	1100	52 11	120 48	ICHe	94	307	4.2	2.2	0.9	L	I
5	5	THUYA L	1250	51 27	120 21	MSb1	96	349	0.8	0.7	0	L	I
6	1	70 MILE	1070	51 17	121 20	IDFb2	75	188	0.4	0.0	0	L	P
6	2	HOLDEN L	1160	51 37	121 31	IDFb2	90	266	0.6	0.0	0.3	L	I
6	3	MONS L	1280	51 40	123 00	SBSa	87	195	0.8	0.0	0	L	P
6	4	KLOAKUT L	1520	51 40	123 30	MS	84	164	0.8	0.0	0	L	P
6	5	CUISSON L	850	52 30	122 23	SBSb	93	315	7.3	0.8	0	L	G
7	1	BATEMAN CR	730	53 53	121 59	SBSj	95	435	1.7	0.4	6.2	L	G
7	2	GOAT R	700	53 30	120 35	ICHk	96	528	1.1	3.2	0.3	L	G
7	3	HOLMES R	910	53 21	119 50	ICHj	91	377	1.9	0.3	6.2	L	P
7	4	VALEMOUNT	1100	52 47	119 19	ICHj	96	338	0.4	–	0.3	L	I
7	5	DAVE HENRY CR	980	52 45	119 05	ICHj	87	466	0.5	–	7.9	L	I
8	1	ATIS CR	1220	52 58	121 55	SBSc	93	290	1.7	0.1	0	M	I
8	2	BAKER L	910	53 03	122 14	SBSc	94	355	28.7	2.0	1.3	L	I
8	3	CAMP 4	1000	53 42	122 25	SBSe2	92	327	4.3	1.5	0	L	I
8	4	NECK L	950	53 15	122 20	SBSe2	96	344	20.0	2.7	0.8	L	I
8	5	WHITES LANDING	670	53 20	122 35	SBSk1	93	255	11.4	0.1	3.4	L	P

Table 1 (Continued).–Ten-year survival, height growth and damage assessments, by region and test site.

Region No.		Test Site Name	Elev. m	Lat.	Long.	BGCzone[1]	Survival[2] %	Height[3] %	Stem Rust[4] %	Needle Cast[5] Score	Root Weevil %	Toppling[6] %	Overall Rating[7]
9	1	DECKER L	930	54 22	125 49	SBSd	97	270	low	–	0.5	M	I
9	2	FRASER L	850	53 57	124 47	SBSd	93	369	2.8	0.8	3.4	M	G
9	3	OOTSA L	1040	53 46	126 50	SBSe	94	296	low	–	0.6	L	G
9	4	TZENZAICUT L	1220	52 39	122 43	IDFb	92	224	3.2	0.0	0	L	P
9	5	BARTON L	790	53 30	123 25	SBSk1	80	273	11.8	0.4	14.7	M	I
10	1	BLACKWATER	730	55 32	123 33	SBS	98	276	low	–	–	M	I
10	2	CARPET L	790	54 36	122 55	SBSe2	99	402	1.1	–	0.1	M	G
10	3	DOG CR	950	54 16	124 24	SBSe1	98	340	4.6	–	0.3	M	G
10	4	WESTON CR	670	55 50	123 42	SBSj2	96	394	1.4	–	1.9	M	G
10	5	SALMON L	950	54 51	123 55	SBSe2	93	309	5.3	–	2.3	M	I
11	1	MCBRIDE L	850	54 04	127 18	SBSe	96	255	low	0.0	0.2	S	I
11	2	CHAPMAN L	790	54 55	126 41	SBSe	92	285	low	0.0	0.1	M	I
11	3	SUSKWA R	640	55 19	127 16	ICHg3	97	342	low	–	5.7	L	G
11	4	NILKITKWA L	760	55 19	126 40	SBSe	98	348	low	0.0	0.2	L	G
11	5	TELKWA R	760	54 37	127 19	SBSe	98	348	low	0.0	0.5	L	G

[1] Biogeoclimatic subzone (Forestry Handbook for British Columbia. 4th edition, 1983, ed. S. B. Watts, Forestry Faculty, Univ. of B.C., Vancouver, B.C.)

[2] 18 trees originally planted.

[3] Height: based on interior provenances only.

[4] % of the trees infected, primarily western gall rust and stalactiform rust.

[5] Needle cast (primarily Lophoclormella concolor):

0	no needle cast or very light infection confined to the most susceptible provenances
0-0.5	light infection
0.6-1.5	moderate infection
1.6-2.5	severe infection
2.5	very severe infection; only the most resistant provenances not infected.

[6] Toppling: L–less than 5% of the trees; M–5-10%; S–more than 10% of the trees.

[7] Overall rating: G–good site; I–intermediate site; P–poor site.

2. Combination provenance–family test. This test, which was intended primarily as a breeding and research arboretum, was planted in 1973 at Red Rock. The trees were four years old. The plantation comprises 778 wind-pollinated families representing 53 inland provenances (Fig. 2). The design includes three fully randomized complete blocks.

Early results from these two projects have been reported by Illingworth (1975, 1978)

Patterns of Geographic Variation and Provenance by Site Interaction

The responses of provenances to environmental gradients and the magnitude of provenance by site interactions are of fundamental importance in the delimitation of seed and breeding zones. Figure 3 shows some of these responses over a wide range of environmental conditions in the Interior. One group of provenances (e.g. Nos. 1, 44, 61, 63, 71, 100, and 104) are seen

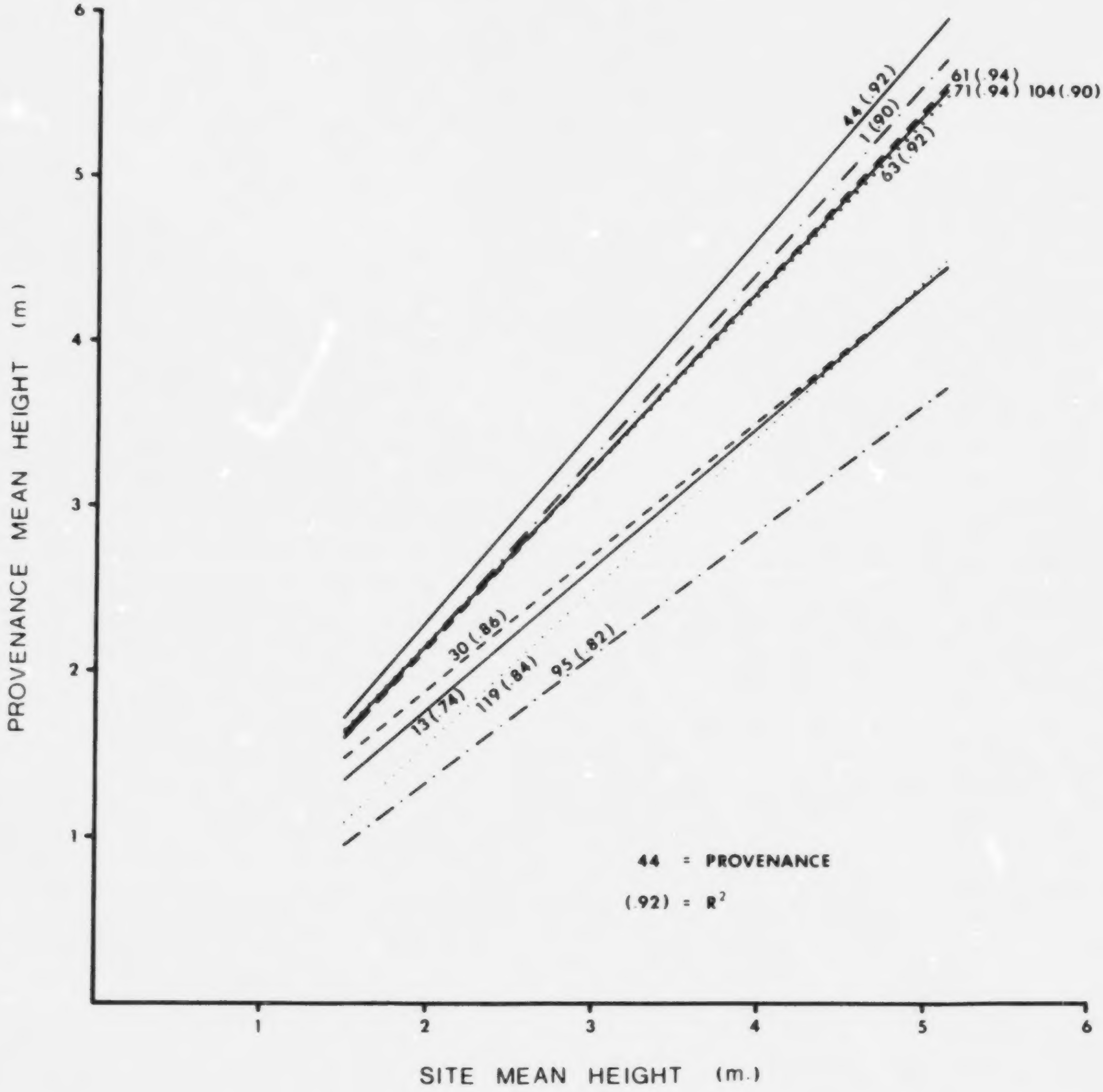

Figure 3. Joint regression of provenance mean height on site mean height to differentiate the two broad geographic groups of provenances.

to be fast growing and relatively stable (high r^2 values); other sources (e.g. Nos. 13, 30, 95, and 119) are much slower growing. Thus, the 140 provenances can be divided (Fig. 1) into two broad groups: (1) those from coastal, far northern and far southern continental climates; and (2) the remaining, more central interior sources. Those of the first group exhibit poor cold tolerance and/or reduced growth; those in the second group, i.e. from Alberta and the B.C. Interior, suffer less cold damage and grow relatively well. These strong differences reflect racial differentiation associated with the geography of the species (Critchfield 1980). Previous analyses (Illingworth 1978; Lindgren *et al.* 1980) have shown that the provenance-by-site interaction contributes little to the total observed variation. Indeed, most of this interaction component resulted from the inclusion of grossly maladapted sources from outside the B.C. Interior (Table 2).

Among the inland provenances, variation in 10-year heights was large, ranging from 1.3 to 2.5 m on poor sites and from 3.9 to 6.3 m on the most productive sites. Total height was only weakly correlated with environmental parameters of seed origin (latitude, longitude, and elevation, Table 3). In general, however, provenances from moist, low- and mid-elevation origins grew fast, and certain of these appear to be broadly adapted to diverse site conditions. Many of these sources showed no signs of phenological maladaptation when moved as much as 400 m in elevation or through 4-5 degrees of latitude.

Table 2.—Summary of F-tests[1] of the effect of site by provenance interaction on total height at age 6, 9, and 13, and leader elongation at age 6 derived from combined variance analyses by individual regions. The first line (1) is based on all provenances and the second line (2) on interior provenances only.

		Leader	Total height		
Region	Age	6	6	9	13
1 Kootenay	(1)	N	**	**	**
	(2)	N	*	N	N
2 Monashee	(1)	N	*	*	**
	(2)	N	N	N	N
3 Thompson P	(1)	N	N	**	**
	(2)	N	N	N	*
4 Upper Columbia	(1)	N	N	*	**
	(2)	N	N	N	N
5 Cariboo	(1)	N	**	**	**
	(2)	N	N	N	N
6 Chilcotin	(1)	**	**	**	**
	(2)	N	N	*	*
7 Upper Fraser	(1)	N	*	**	**
	(2)	N	N	N	N
8 Willow R	(1)	N	N	**	N
	(2)	N	N	N	N
9 Nechako P	(1)	N	N	*	N
	(2)	N	N	N	N
10 MacKenzie	(1)	*	**	**	**
	(2)	*	*	*	N
11 Takla	(1)	N	N	N	N
	(2)	N	N	N	N

[1] N–not significant;
* –significant at 0.05 level;
**–significant at 0.01 level.

Possibilities for Genetic Improvement

Provenance data of the type reported here are a valuable asset in the development of a breeding strategy. A knowledge of the amount and distribution of within-species variability for desirable traits allows one to more intelligently structure breeding populations and plan breeding and testing activities. Also, identification of superior and genetically stable stands provides immediate opportunities for capturing genetic gains from: (1) phenotypic selection within these stands, and (2) combined provenance, family, and individual tree selection from within a provenance-family plantation such as that at Red Rock (Fig. 2). As an example, two selection schemes, using the Red Rock plantation, are presented with associated estimates of genetic gain (Table 4). Both schemes clearly demonstrate the need to consider provenance variation in any program for the genetic improvement of lodgepole pine. In both, the best six provenances contributed more than half of the selected individual trees and families, the Larch Hills source (No. 72) alone contributing nearly one-quarter of the tallest 200 trees; while in the second scheme, 14 out of the 15 families from Larch Hills and Inonoaklin (No. 57) were among the 100 selected families.

Table 3.—Correlation of total height at age 13 with latitude, longitude, and elevation of the provenance origin, and the proportion of the among-provenance variation accounted for by latitude, longitude, and elevation (R^2).

	Correlation with			
Region	Lat[1]	Long	Elev	(R^2)
1 Kootenay	−.22	−.22	−.48*	.39
2 Monashee	−.29	−.57**	.15	.37
3 Thompson P	−.49*	−.50**	−.20	.36
4 Upper Columbia	−.42**	−.29	−.05	.27
5 Cariboo	−.19	−.27	−.27	.22
6 Chilcotin	−.21	−.30	−.36	.29
7 Upper Fraser	−.49**	−.22	−.17	.46
8 Willow R	−.40*	−.26	−.10	.24
9 Nechako P	−.47*	−.53**	−.17	.46
10 MacKenzie	−.03	−.00	−.37*	.24
11 Takla	−.39*	−.23	−.12	.24

[1] * –significant at 0.05 level.
**–significant at 0.01 level.

Table 4.—Contribution of individual provenances and predicted genetic gain under two different selection schemes.[1]

Selection scheme	No. of contributing provenances No.	Contribution by the top 6 provenances %	% above local provenances Volume %	% above local provenances Height %	Predicted genetic gain Volume %	Predicted genetic gain Height %
1	30	67	84	33	15.8	6.7
2	22	66	77	29	11.7	4.9

[1]Scheme 1: Select 200 tallest trees from the plantation without regarding provenances and families.
Scheme 2: Select 100 tallest families and then select 2 tallest trees from each family.

Site to Site Variation

Provenance tests, such as those reported here, provide unbiased comparisons of site and seed source productivities and permit assessment of the biological risks involved in wide seed transfers. To justify investment in intensive silviculture, including tree improvement, site productivities must be high and biological risks (insect and disease damage) low. Substantial differences in site productivity and damage hazard were found to exist among the 55 sites measured. The 55 sites were divided into three groups according to observed growth and risk potentials (Table 1). The majority of good sites can be characterized as moist, low- to mid-elevation and without excessive snow accumulation. In general, they are below 1,000 m in the north and below 1,600 m in the southern interior. Sites in the moist Columbia Forest Zone (Rowe 1972) permitted the best growth, but several were susceptible to severe pest infection, notably needle cast diseases. Many trees, especially those of high-elevation origins, showed signs of declining vigor after 10 years in the field. However, sites at higher elevations or in the drier interior plateau regions probably do not justify the expense of intensive silvicultural manipulation.

Conclusions and Implications

Marked differences in site and provenance productivities suggest the importance of site selection for investment in intensive silviculture, and the potential for increasing the productivity through selection and breeding. Obviously, tree breeders and silviculturists, in their search for productive seed sources and parent trees, need only concern themselves with provenances of the inland form of the species (Fig. 1). Although low site by provenance interaction (Table 2) suggests the broad transferability of lodgepole pine, at this stage of testing prudence calls for a conservative interpretation in the operational application of early results. However, it is evident that local provenances are not necessarily the most desirable, and the opportunity for planting genetically improved trees will be lost if we inflexibly confine ourselves to using only local seed sources—particularly for productive sites with relatively low biological risk (Table 1).

The potential of wind-pollinated progeny as source material for re-selection is evident (Table 4). Such progeny, which can be quickly and cheaply gathered, provides the only practical and economical alternative for generating a large base population for multiple-trait selection—considered by us to be the most practical approach for combining desirable traits.

One major objective of provenance research is to provide guidelines for seed transfer and delineation of seed and breeding zones. In the Pacific Northwest, seed transfer guidelines are primarily designed to minimize the risk of cold injury, based on results of short-term tests in nursery or controlled environments. Our results indicate that cold hardiness alone is not adequate for determining the transferability of a provenance. For example, high-elevation provenances and provenances from the Yukon and northern British Columbia, although apparently winter hardy, grow slowly and are highly susceptible to needle cast at most sites. In fact, most of the interior provenances (Fig. 1) are capable of recovery from non-recurring frost injury; damage caused by snow press, disease, and other environmental stress is often more severe than frost injury. The adaptability of a population cannot be adequately described until it has been subjected to a test by all the physical and biological components of the whole environment. Despite its expense, a full-scale long-term provenance test can be justified on the grounds of its long-term benefit to reforestation and genetic improvement.

In regulating seed transfer, it is also important to differentiate sites with low biological risk from those with high biological risk (Adams and Campbell 1981). For the former, as characterized by the good sites and some of the intermediate sites (Table 1), a broad transfer involves little risk, but will allow the planting of productive non-local sources and thus enhance the productivity of the plantations. For the latter, seed transfer must be restricted to the planting of either local seed, or non-local seed that has certain desirable traits, such as resistance to snow press (for sites in the snow belt) or to needle cast (for sites with frequent needle cast infection).

Seed zones currently in use in the B.C. Interior were delineated primarily on the basis of broad ecological and administrative units, rather than in accordance with the species' biological limitations and potential for safe manipulation. Information from the present studies will permit adjustment of seed transfer rules and seed orchard zones to reflect the more broadly adapted nature of lodgepole pine, particularly in the more productive portions of the B.C. Interior.

The results have shown that seed transfer may be more critical along altitudinal gradient than along the latitude or longitude, and that planting of seed from low-elevation sources at higher elevation sites is of advantage. However, precise delineation of elevational intervals, within which seed can be freely moved without the risk of cold injury or damage caused by environmental stress, is a difficult task. Strategies will obviously vary from region to region. Rehfeldt (1983*a,b*), for example, recommends a 200-m elevational transfer limit for lodgepole pine in northern Idaho. Preliminary indications from the British Columbia trials suggest the feasibility of somewhat wider elevational seed transfer.

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PROSPECTS FOR TREE IMPROVEMENT IN LODGEPOLE PINE

G. E. Rehfeldt

ABSTRACT

To realize genetic gains in productivity, tree improvement must maintain both adaptedness and the quality of secondary economic traits. Adaptation is partially reconciled by establishing breeding zones within which populations are adaptationally similar. For lodgepole pine of northern Idaho, for example, breeding zones should be elevationally narrow (200 m). Genetic variability within zones portends substantial genetic gains, including increases in height of 10 to 15 percent. Traits, however, are not inherited singly. Selecting a breeding population for height alone will increase substantially the number and length of branches, the number of whorls, and the duration of shoot elongation. Thus, gains in growth will be accompanied by maladaptation and by a deterioration in quality. The breeding strategy must seek the optimum compromise among growth, adaptation and form.

INTRODUCTION

Progress in plant breeding requires genetic variability. Consequently, the large differences in height, growth rates, and form commonly exhibited by lodgepole pine in even-aged stands suggests nearly unlimited possibilities for tree improvement (Rehfeldt *et al.*, 1980). These possibilities, however, must be tempered. First, variation among trees is influenced by environment as well as by genetics. This means that only a portion of the differences observed among wild trees can be realized as genetic gains from a single generation of selective breeding. And secondly, realization of genetic gains in productivity requires a breeding strategy that maintains both adaptedness and the quality of secondary economic traits.

Thus, an effective breeding strategy must be consistent with the ecological genetics and quantitative genetics of the species. Principles of ecological genetics offer a means of assuring that trees are adapted to the environment in which they are planted. The principles of quantitative genetics allow genetic gains to accrue without inadvertent degeneration of other adaptive or economic traits.

ECOLOGICAL GENETICS

Through the ages, natural selection has physiologically attuned populations to their environment. For each population there exists, therefore, an optimal range of environments for which individuals and their offspring are adapted (physiologically attuned). The movement of individuals beyond the optimal range results in maladaptation, the degree of which depends on the transfer distance in relation to the size of the optimal environment. Maladaptation can be expressed in responses that range from mortality to subtle losses in productivity. This means that genetic gains from tree improvement can accrue only after the control of maladaptation. To accomplish this, tree improvement takes place within breeding zones. When breeding zones reflect adaptive differentiation of populations, the effects of maladaptation are reconciled.

Delineation of breeding zones assumes prior understanding of patterns of adaptive variation among populations. Such knowledge is gained by comparing the performance of populations growing in common environments where genetic variability can be observed directly. When genetic patterns of variation correspond to environmental gradients, adaptive variation can be assumed.

Provenance tests of lodgepole pine conducted in Canada, Scandinavia, and the United States generally depict population differentiation along relatively steep clines; differentiation occurs across relatively small environmental gradients. In the United States, for example, populations from Idaho and Montana (Rehfeldt, 1980; Rehfeldt and Wykoff, 1981) are genetically differentiated for a variety of traits relating to growth potential and cold hardiness. Logistic models of cold injury (fig. 1) illustrate tremendous genetic variation among populations:

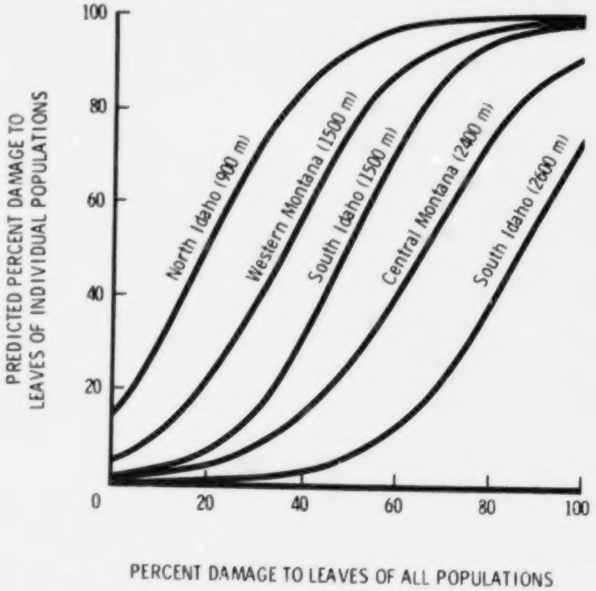

Figure 1. – Response curves of freezing damage according to the severity of the freezing treatment (mean injury) for five provenances that illustrate a variety of observed responses (from Rehfeldt, 1980).

for instance, a freeze that injures 50 percent of the trees from all populations is expected to damage only 5 percent of the trees from high elevations in southern Idaho while damaging nearly 95 percent of the trees from low elevations in northern Idaho. Similarly, populations express tremendous variation in the periodicity of shoot elongation (fig. 2). Populations from severe environments elongate at a slow rate, cease elongation early; and, therefore, tend to be short. In contrast, populations from mild environments elongate rapidly for a long period of time and, thereby, tend to be tall.

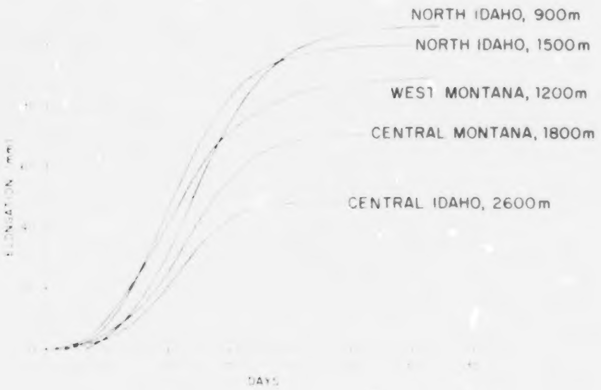

Figure 2. – Models of 2-year shoot elongation for five populations that illustrate genetic variation in the initiation, rate, duration, cessation and amount of elongation (from Rehfeldt and Wykoff, 1981).

The same studies present simple correlations between cold injury and variables reflecting periodicity of shoot elongation (rate, duration, cessation, and amount of elongation) that are high and negative (r = −0.70). Populations from mild environments are of high growth potential and low hardiness, while populations from severe environments are of high hardiness but low growth potential. Thus, adaptation of populations to heterogeneous environments of the Rocky Mountains can be viewed as a balance between selection for high growth potential by mild environments and selection for high cold hardiness by severe environments. As a result, four geographic zones, (northern and southern Idaho, western and central Montana) plus elevation of the seed origin account for as much as 78 percent of the variance among populations for the variables tested. Elevation, however, accounts for approximately three times as much variance as geography.

In addition, populations from northern Idaho express marked differences for susceptibility to diseases (Hoff, 1984). In a single planting at low elevation, populations differed by as much as 35 percent in the incidence of needle cast (*Lophodermella concolor*), and by 19 percent in the incidence of gall rust (*Endocronartium harknessii*). Although genetic variation in resistance to gall rust showed no discernible geographic, physiographic, or ecologic patterns, the simple correlation between the incidence of needle cast and elevation of the seed origin was strong (r = 0.82); thus, the higher the elevation of the seed origin, the greater the incidence of needle cast occurring on a site at low elevation.

Thus, adaptive variation in cold hardiness, disease resistances, and periodicity of shoot elongation is readily detected among populations. Differentiation, moreover, is closely related to the elevation of the seed source and is relatively weakly associated with geography. The available studies, however, are of insufficient scope for describing exactly how far (geographically, physiographically, or ecologically) seed can be transferred before maladaptation begins limited productivity. They are, therefore, inadequate for delineating breeding zones.

A recent assessment of adaptive variation among populations from northern Idaho (Rehfeldt, 1983) involved populations originating within 55 km (35 mi) of the field test sites. Genetic variation, therefore, would be independent of geography. Populations expressed prounounced differentiation for a variety of traits related to cold hardiness and growth potential. The elevation of the seed source, moreover, was the only variable that could be related to differentiation. In fact, elevation accounted for as much as 89 percent of the variance among populations (fig. 3). The relationships, however, were definitely nonlinear.

Both the strength and nonlinear form of the relationship between population performance and elevation of the seed source determine the potential consequences of seed transfer. First, losses in productivity accrue from transfers of two types (fig. 4). When seed is moved upward in elevation, the transferred material is of lesser hardiness than the local and is, therefore, susceptible to greater freezing injury; and, when seed is moved downward, the transferred material is of lesser growth potential. Secondly, the potential consequences depend on the elevation at which the transfer takes place. For instance, when seed from 1000 m (3200 ft) is transferred 500 m (1600 ft), the transferred material is expected to differ from the local by about 12 percent in freezing injuries and by about 18 percent in 4-year height. But, transfers of the same distance for seeds originating at 1500 m (4900 ft) are associated with differences exceeding 25 percent in freezing injuries and about 30 percent in height.

Because of the potential consequences of the elevational transfers of seed, breeding zones for lodgepole pine in northern Idaho should be limited to 200 m (650 ft) (Rehfeldt, 1983). Although estimates of the appropriate geographic extent of breeding zones are not yet available, for northern Idaho, zones undoubtedly will be less confining administratively than the elevational limits.

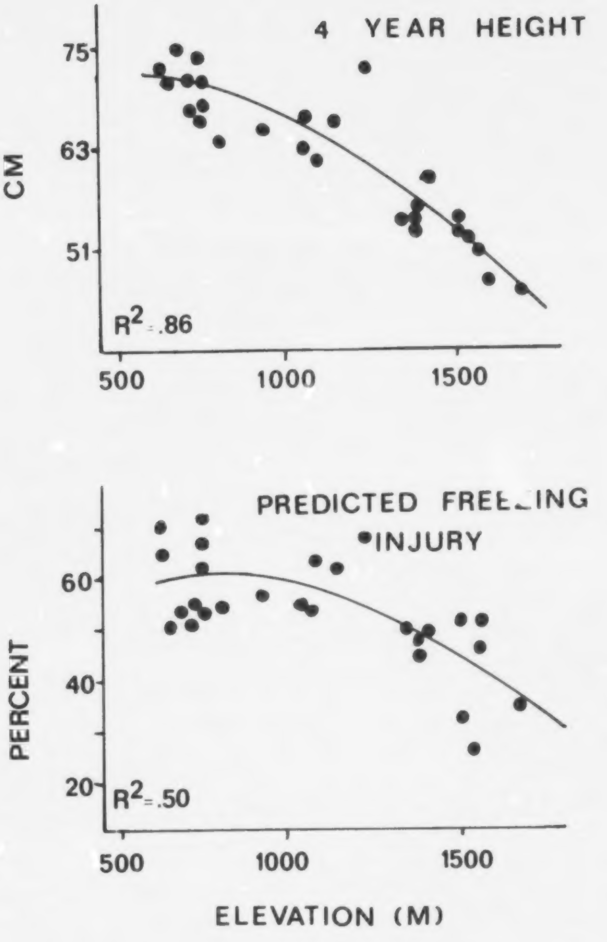

Figure 3.—Relationship of mean values of growth and cold hardiness for populations from northern Idaho with the elevation of the seed source (from Rehfeldt, 1983).

QUANTITATIVE GENETICS

Recent analyses[1] provide a quantitative evaluation of the possibilities for tree improvement within single breeding zones.

The analyses involved 10 traits reflecting growth, adaptation, branching, and form of 6-year old trees from 10 families within each of eight populations from the inland northwest United States. Substantial phenotypic and genetic variances were detected for most traits. As a result, heritabilities (the proportion of the phenotypic variance attributable to genetics rather than environment) or moderate size translate into substantial genetic gains for single breeding units (table 1).

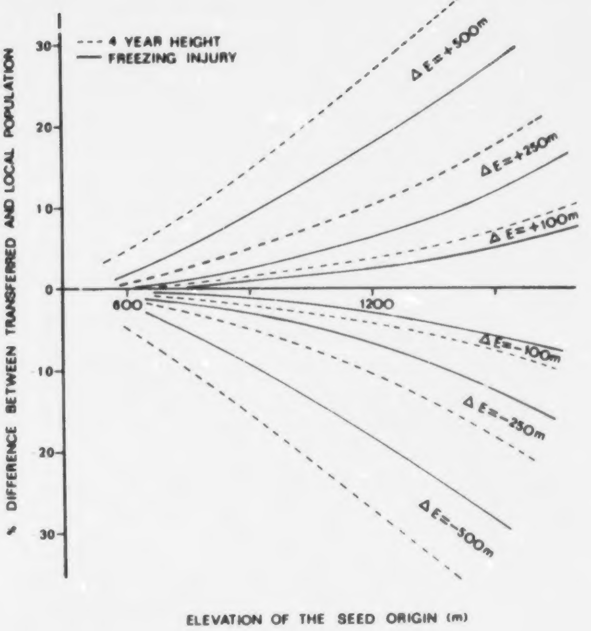

Figure 4.—Expected differences, as reflected by regressions in figure 3, between local populations and populations resulting from the transfer of seeds across various elevational intervals (ΣΔ) in northern Idaho (from Rehfeldt, 1983).

Table 1.—Estimates of heritabilities, genetic gains from univariated selections for height and correlated responses to univariate selections within breeding zones of lodgepole pine. Heritabilities are based on half-sib variances of individual trees. Genetic gains and correlated responses refer to mass selection and are expressed as percentage increases expected next generation at a selection intensity of i = 1 (from Rehfeldt, see text footnote 1)

Trait	Heritability (h^2)	Genetic gain (%ΔG/i)	Correlated response (%CR/i)
6-year height	.22	5.1	--
6-yr. elongation	.17	4.5	1.5
Early growth[1]	.15	6.4	−.0
Late growth[2]	.19	11.9	2.5
Branch length	.15	4.0	1.1
Branches	.13	4.6	−.0
Crown width	.25	6.6	1.5
Leaf length	.36	7.8	.3
Whorls	.17	3.6	.1

[1] The amount of 6-year elongation that occurred during the first week of growth.

[2] The amount of 6-year elongation that occurred after midsummer.

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[1] Rehfeldt, G. E. Genetic variances and covariances in *Pinus contorta*. In preparation.

These gains (table 1) are to be realized in subsequent generations after the interpollination of select trees. The gains are presented as percentage increases expected from mass selection (selecting the best performing individuals without regard to family) per unit selection intensity (i). This selection intensity is a function of the proportion of the unselected population that is selected for inter-breeding according to the results of progeny tests. The selection intensity depends on characteristics of the normal curve: one unit selection intensity requires that about 38 percent of the tested population be selected for breeding; two units require 6 percent; and three units, about 1 percent (Falconer, 1960).

For the statistics presented in table 1, mild levels of mass selection (i = 1) for height alone should yield a 5 percent gain in 6-year height; strong selection (i = 3) should yield 15 percent gains within breeding units. Most of the traits studied (table 1) are under relatively strong genetic control and are, therefore, capable of relatively large responses to artificial selection. In addition, Hoff (1984) has detected substantial genetic variation among and within families for resistance to needle cast. With a heritability for individuals of 0.31, the potential is high for breeding resistant populations for areas of high hazard.

This means that traits related to productivity, adaptedness, form, branching, and pest resistance are all governed by abundant genetic variability. All are, therefore, subject to considerable genetic manipulation. Unfortunately, individual traits are not inherited singly. For the data summarized in table 1, strong genetic correlations (about 0.7) link height, branch length, crown width (fig. 5), and late growth. Height is also related to the number of whorls produced in year 6, and, consequently, to the number of branches on the current shoot, but these relationships were not expressed by genetic correlations because of a low phenotypic variance of whorl numbers within the families sampled (81 percent of the individuals had two whorls).

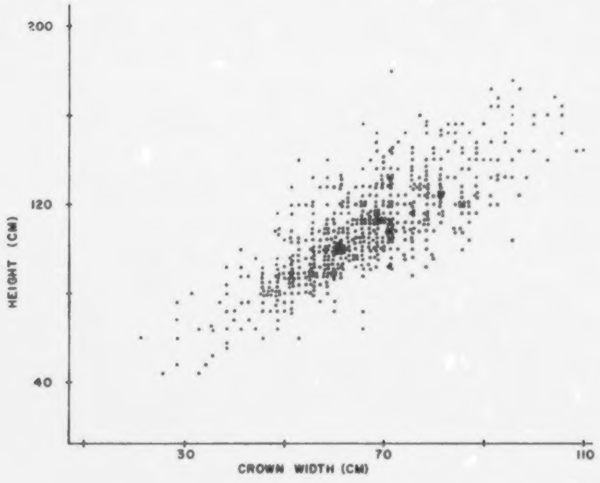

Figure 5. – Relationship between 6-year height and crown width for individual trees from 10 families within a single population (from Rehfeldt, see text footnote 1).

Strong genetic correlations imply that correlated responses in secondary traits will accompany univariate selection programs. Thus, breeding populations, selected according to height alone, will provide offspring of greater growth potential than that of the parental generation, but will also provide offspring with longer branches, wider crowns, more whorls, more branches, and a greater proportion of late growth. The correlated responses expected in the progenies of trees selected (i = 1) according to height are detailed in table 1. The responses, however, underestimate the expected increases in whorls and branches, largely because low levels of phenotypic variance produced insignificant genetic correlations. Nevertheless, if the tallest 10 percent of the trees had been selected for a breeding population, the proportion of trees with 3 whorls on the 6-year shoot would have increased from 10 percent to 30 percent. The average selected tree would also have had 2.5 more branches on the current shoot than the unselected.

A challenge thus exists for the tree breeder: to improve productivity while either maintaining or improving adaptedness, resistances, or economic traits of secondary importance. To meet this challenge, selection indices (reviewed by Lin, 1978) are available to the breeder. Selection indices are of the form:

$$I = b_1 X_1 + b_2 X_2 \ldots + b_n X_n,$$

where I is an index value calculated for each tree; X's are phenotypic measurements for various traits; and b's are the selection coefficients that weight individual traits. Restricted selection indices provide values of b such that gains in productivity can be maximized while correlated responses in other traits are restricted. Trees to be represented in breeding populations are selected according to composite scores represented by values of I.

Figure 6 illustrates the potential genetic gains expected in the height of lodgepole pine trees when the correlated responses of branch length, crown width, and late growth are restricted varying amounts. The figure also presents the values of b required for achieving various levels of restriction. Levels of restriction were chosen according to whether traits were economic or adaptive. Branch length and crown width are secondary economic traits; both are correlated with branch diameter and stem diameter (Fryk, 1980). Consequently, models (fig. 6) are presented that provide for either zero or complete restriction of the correlated response expected in these variables. In contrast to these economic traits, late growth, the amount of shoot elongation that continues into mid-summer, is a key trait in a sequence of developmental events that must be synchronized with the frost-free period. If the duration of shoot elongation is increased, leaf maturation, bud development, and lignification are delayed; and the susceptibility to frost injury is increased. Late growth is, therefore, an adaptive trait. Because it is imperative for adaptedness to be maintained, models presented in figure 6 greatly restrict the correlated response in late growth.

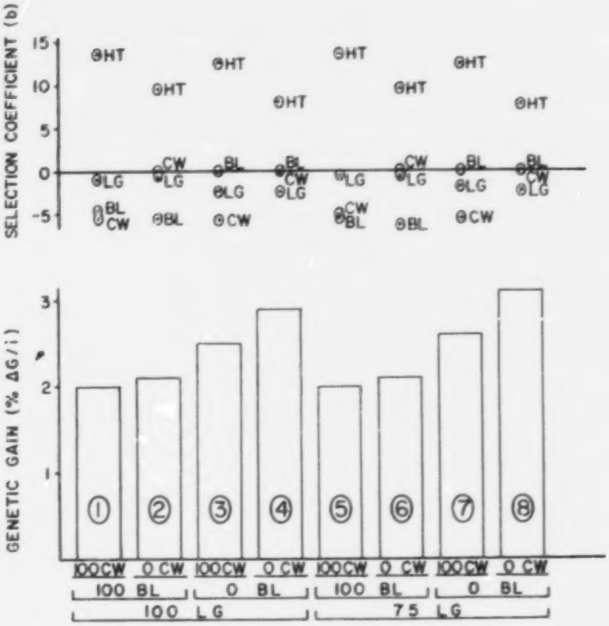

Figure 6.—Coefficients for selection indices and associated genetic gains (%Δ) in height (HT) expected under various indices (bar graphs) restricting the correlated response of branch length (BL), crown width (CW), and late growth (LG). Gains are estimated at selection intensities of i = 1 (from Rehfeldt, see text footnote 1).

For the indices presented in figure 6, severe restriction of late growth also held constant the number of whorls and, consequently, the number of branches. It is not known, however, whether this result is unique to the particular sample or is characteristic of the genetic system of the species.

Finally, the correlated responses for crown width and branch length (table 1) represent expected changes associated with genetic gains in height of 5 percent (i = 1). Responses for these two traits are almost precisely those expected in trees 5 percent taller than the mean. Rather than representing degeneration, the correlated responses thus reflect the maintenance of present quality. This means that restriction of the correlated responses in crown width and branch length (fig. 6) represents improved quality of secondary economic traits.

Regardless, when correlated responses are restricted, genetic gains in productivity are reduced (fig. 6). By holding constant adaptedness (late growth) and improving secondary economic traits (branch length and crown width) genetic gains in height are reduced from 5 percent to 2 percent per unit selection intensity. Even with intense selection, gains of about 8 percent (i = 3) seem to be the maximum. To accept larger gains is to compromise quality or risk maladaptation.

An alternative to breeding strategies based on index selection involves the search for the crop ideotype (Donald, 1968). The ideotype is represented by the ideal and, therefore, rare individuals in which genetic correlations have been broken; this allows many desirable traits to occur in individual trees. Karki (1983) attests to the feasibility of developing races of *Picea abies* and *Pinus sylvestris* that combine fast growth with fine branches and narrow crowns which, thereby, can be grown in dense plantings. Indeed, scatter diagrams (fig. 5) purport the existence of tall lodgepole pines that have much narrower crowns than most trees of similar height. These trees are, however, extremely infrequent. Consequently, a breeding strategy based on the idotype seems most feasible as a secondary approach. Nevertheless, the presence of such trees raises the possibility of combining traditional strategies with that of Karki (1983): develop selection indices that hold growth constant while maximizing a reduction in crown width. Gains in productivity are realized, then, by cultivating dense stands.

Regardless of the approach, strong genetic correlations demand that a breeding strategy skillfully manipulate genetic variability. The strategy must seek the optimum compromise between growth, adaptation, and form.

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SITE CLASSIFICATION

ECOLOGICAL CLASSIFICATION OF LODGEPOLE PINE IN THE UNITED STATES

Leonard A. Volland

ABSTRACT

Literature relating to ecological classification of lodgepole pine in the United States is reviewed with emphasis being placed on the last 15 years. The review discusses ecological status of the species and importance of lodgepole pine site classification to resource management considerations. These classifications usually relate to the successional status of lodgepole pine and how the investigator perceives the position of the species in that context.

The species occurs in three distinctly different ecological niches across its geographic range: (1) as a seral species to more shade tolerant tree species, (2) as a relatively stable codominant with one or more other species, and (3) as the only tree layer dominant. Characteristics which influence the seral status of lodgepole pine include its wide ecological amplitude, the frequency of stand disturbance and size of the area being disturbed. Successional development where lodgepole is either seral or persistent usually follow multiple pathways depending upon associated species and stand history. Climax sites have topographic and/or edaphic characteristics considered too harsh for successful establishment of other species.

A stratification of lodgepole environments permits management to be directed to those sites where resource values, risk to stand deterioration, or opportunities for species manipulation are the greatest. The plant community is one way of achieving this stratification since information affecting lodgepole management decisions (critical environmental controls and successional trends) are inherent to the community. Another approach is to correlate population studies of size or age distributions by species with stand historical information.

INTRODUCTION

Site classification of lodgepole pine (*Pinus contorta* Dougl.) has progressed quite rapidly over the ten years which followed the last lodgepole symposium. Much of the classification work has been associated with synecological studies conducted on a systematic basis throughout the western United States (Pfister 1977, Franklin 1980). As a result of this work, more specific descriptions are now available as to those environments in which lodgepole pine has been defined (after Pfister and Daubenmire 1975) as a seral, persistent seral, or climax species.

Over the same period studies in species autecology and population dynamics have been published which further clarify some functional processes which operate in lodgepole-dominated ecosystems. As a result of these two different, but synergistic, approaches to species ecology we have a better understanding of lodgepole pine behavior and its position in a classification system.

CONCEPTS OF CLIMAX

Pertinent to any ecological classification of lodgepole pine is a definition of what constitutes climax vegetation. A common definition of climax is the plant community that appears as self-regenerating without evidence of a subsequent and different community being developed (Daubenmire 1968). Some characteristics of a climax plant community as given by Steward and Hann (1983) are (1) species in equilibrium with the physical environment and each other so that interspecific competition is at a maximum, (2) stand structure and composition reach a dynamic, but stable endpoint, (3) variations in the stable community occur as fluctuations attributed to individual mortality and yearly climatic patterns. Mueller-Dombois and Ellenberg (1974) suggest this dynamic stability may extend over several decades in which species composition and structure remain relatively constant.

Authors working in lodgepole pine ecosystems have, on occasion, redefined dynamic stability within the context of their experience. Moir (1969) defined climax for lodgepole pine forests as those showing no apparent change in proportions of tree species after 100 years of pine dominance. Romme (1982) suggested a steady-state system may not occur for subalpine forests containing lodgepole pine because periodic, large, destructive fires give cyclic, long-term changes in community structure and function. Steady-state may not ever occur in forest systems subjected to periodic perturbation (Whitehead 1982).

The term "potential natural vegetation" (PNV) has been proposed for vegetation that develops under recurring perturbations. Potential natural vegetation is defined as vegetation that would develop if all successional sequences were completed without interference by man under present climatic and edaphic conditions (Mueller-Dombois and Ellenberg 1974). Present environmental conditions include those conditions created by man as an important environmental influence but not an environmental manipulator. For instance, the influence of fire suppression on stand development has prompted ecologists and foresters to reevaluate the seral status of lodgepole pine in some environments. The PNV approach projects the existing vegetation into the future and accepts stabilized, presumably seral, communities as approximations of potential (Schlatterer 1983).

The classification of lodgepole pine communities in western U.S. has generally proceeded under the plant association approach. The plant association was defined by Daubenmire (1968) as the aggregation of all climax stands having similar habitat potential and essentially the same dominant species in each lifeform layer. This approach is represented by descriptions of habitat types published for the northern and central Rocky Mountains (Pfister *et al.* 1977; Hoffman and Alexander 1976, 1980, 1983) and the plant associations in the Pacific Northwest (Hall 1973, Hopkins 1979, Volland 1982, Hemstrom *et al.* 1982, Williams and Lillybridge 1983). Habitat types are all land areas potentially capable of supporting the same plant association (Daubenmire 1968). Plant associations which have the same potential dominant species at climax are combined into a broader classification unit called series, as illustrated in Table 1. The term community type is often used to identify a recurring vegetation where the potential natural steady state (climax) has not been demonstrated or is uncertain (Daubenmire 1976, Hall 1973).

Plant community classification and mapping of habitat types serve different purposes. A description of plant associations identifies the vegetation units that have been classified. The mapping of these associations involves delineating land areas which are thought to have similar vegetative potential. These mapped units are often referred to as habitat types since the focus is toward a landscape unit rather than a vegetation unit. The conceptual differences between association and habitat type should be recognized as one reads the classification literature.

The classification status of lodgepole pine as a seral, persistent seral, or climax species in the current literature is largely a result of the investigator's ecological philosophy. If a species is perceived as seral, then stands containing that species might not be viewed as successionally stable representations of the potential natural vegetation. An ecological philosophy that

Table 1. Number of classified plant associations and community types listed by series in Western U.S. in which lodgepole pine is considered a seral species. (Literature search 1973 through 1983).

	NUMBER OF		
SERIES	**ASSOCIATIONS**	**COMMUNITY TYPES**	**REFERENCES**
Abies lasiocarpa	39	0	Hall 1973; Pfister *et al.* 1977; Hoffman & Alexander 1976, 1980, 1983; Schimpf *et al.* 1980; Steele *et al.* 1981, 1983; Williams & Lillybridge 1983; Cooper *et al.* 1983; Henderson *et al.* 1976, 1977; Mauk & Henderson 1984
Picea engelmannii	13	0	Hoffman & Alexander 1976; Pfister *et al.* 1977; Steele *et al.* 1981, 1983; Mauk & Henderson 1984
Picea pungens	1	0	Mauk & Henderson 1984
Tsuga mertensiana	6	0	Pfister *et al.* 1977; Zeigler 1978; Hopkins 1979a; Volland 1982; Hemstrom *et al.* 1982; Cooper *et al.* 1983
Abies amabilis	3	0	Williams 1978; Hemstrom *et al.* 1982
Tsuga heterophylla	1	0	Pfister *et al.* 1977; Cooper *et al.* 1983
Thuja plicata	1	0	Pfister *et al.* 1977; Cooper *et al.* 1983
Abies magnifica var. shastensis	4	0	McNeil 1976; Zeigler 1978; Hopkins 1979a; Volland 1982
Abies concolor	8	0	McNeil 1976; Hopkins 1979b; Volland 1982; Henderson *et al.* 1977
Calocedrus decurrens	1	0	Zeigler 1978
Abies grandis	12	0	Hall 1973; Pfister *et al.* 1977; Williams 1978; Steele *et al.* 1981, 1983; Johnson 1981; Cooper *et al.* 1983
Pseudotsuga menziesii	16	0	Hoffman & Alexander 1976; Pfister *et al.* 1977; Roberts 1980; Steele *et al.* 1981, 1983; Johnson 1981; Williams & Lillybridge 1983; Cooper *et al.* 1983; Henderson & Peter 1983; Mark & Henderson 1984
Pinus ponderosa	6	0	Volland 1982; Henderson *et al.* 1977; Mauk & Henderson 1984
Pinus contorta	0	18	Hall 1973; Cooper 1975; Hoffman & Alexander 1976; Pfister *et al.* 1977; Hopkins 1979b; Johnson 1981; Steele *et al.* 1981, 1983; Volland 1982; Cooper *et al.* 1983; Henderson *et al.* 1977; Mauk & Henderson 1984
Populus tremuloides	4	3	Hoffman & Alexander 1980; Youngblood & Mueggler 1981; Mueggler & Campbell Jr. 1982
Total	114 +	21 = 135	

perceives succession as unidirectional toward a steady state end point rather than cyclic within the context of a manipulative environment will choose sample stands which do not have "seral" species as a layer dominant.

FOREST SUCCESSION

Ecological succession has been defined by Odum (1969) as an orderly, reasonably directional process of community development which results in modification of the physical environment and, eventually, a stabilized ecosystem often referred to as "climax" in terrestrial systems. Forest successional patterns are often discussed in terms of differences in shade tolerance between species or trends in tree age or size class data with the use of population histograms (fig. 1). The *inverse J curve* has a decreasing number of stems with increasing tree age or size and indicates a self-perpetuating population. The *bimodal* curve shows two peaks of stem density or age from reproduction pulses or gap phase replacement and is also typical of self-perpetuating populations of a species.

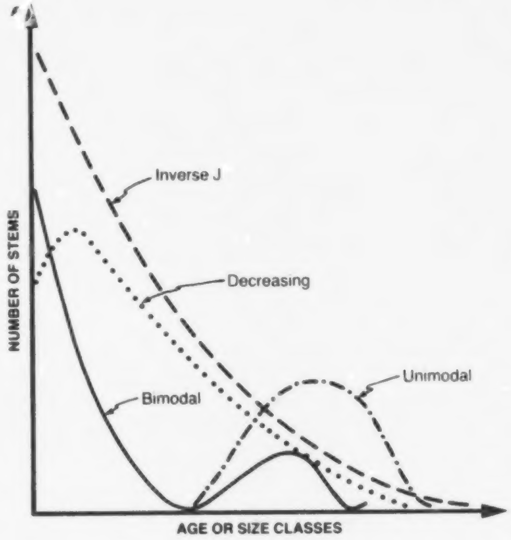

Figure 1.—Idealized population distribution curves. (after Whipple and Dix, 1979)

Figure 1.–Idealized population distribution curves (after Whipple and Dix, 1979).

The *decreasing* curve lacks the recruitment in younger or smallest trees and can indicate a seral species. The *unimodal* curve suggested a seral species because a peak stem density occurs in older or larger tree sizes which, if continued, will lead to species extinction. The unimodal curve may also indicate a prolonged gap phase regeneration cycle which is regulated by the frequency of stand perturbations. Lodgepole pine survives the perturbation (as underburning) at the expense of more shade tolerant species which are intolerant to the disturbance.

Population studies have indicated pine expresses several population histograms. Day (1972) has interpreted lodgepole as a seral stand component with a unimodal, bell-shaped curve growing with the more shade tolerant *Picea engelmannii* (a bimodal curve) and *Abies lasiocarpa* (an inverse J curve). Despain (1983) suggested lodgepole as a persistent dominant with an inverse J distribution either where repeated burning removes fire intolerant species or where environmental factors prevent establishment and growth of other species. Lodgepole has been interpreted in Colorado as a climax species with a bimodal age distribution in stands not successfully regenerated to more shade tolerant spruce and subalpine fir (Whipple and Dix 1979).

LODGEPOLE PINE AUTECOLOGY

Some knowledge of the autecological attributes of lodgepole pine are basic to understanding the environmental behavior of the species and its position in any classification scheme. Lodgepole pine is one species which definitely challenges the imagination of any ecologist who contemplates the validity of climax plant communities, steady-state dynamics, ecosystem stability or unidirectional succession. If one could describe plant species by their apparent behavior, lodgepole pine could be viewed as an opportunist of the plant world. The species is capable of growing over a broad range of environmental conditions. Lodgepole pine reproduction tolerates high surface soil temperatures, extremely low air temperatures, and water-saturated soil profiles better than most associated conifers. It is drought-resistant and fairly intolerant to shade. The species produces abundant seed in one to three year intervals and has the ability to develop fertile cones by the fifth year in open grown stands and by the twentieth year in dense stands. Lodgepole seeds are fairly heavy; the majority are dispersed within 61 meters (200 feet) of an available seed source (Dahms 1963).

Lodgepole has a closed (serotinous) cone habit over a significant portion of its geographical range. Cone serotiny permits seed to survive major disturbances and yet be available for dispersal onto favorable seedbeds. Favorable seedbeds are defined as mineral soil or disturbed litter, relatively free of competing ground vegetation and overhead shade. The site disturbance which results from intense burning (either natural or man-caused), stand harvest and subsequent slash disposal, or severe windthrow can create seedbeds conducive to lodgepole establishment. The timing and geographic extent of the disturbance becomes more critical in the absence of cone serotiny. Large burns and clearcuts are slowly regenerated with lodgepole in the absence of this seed source (Cochran 1973).

Lodgepole pine is not exceptionally long-lived although its longevity varies across its geographical range. Persistence in mixed species stands has been reported as low as 120 to 150 years (Antos and Habeck 1981, Cattelino *et al.* 1979) to an extreme of 350 to 400 years (Romme and Knight 1981). Other studies indicated a longevity from 200 years to 240 years

(Kumler 1969, Day 1972) depending upon location. The longevity of lodgepole is fairly short as compared to its more shade tolerant competitors. Longevity is important when it is evaluated with frequency of stand perturbation. A perturbation frequency less than the longevity of lodgepole can maintain the species as a persistent member of the plant community. Perturbations in excess of lodgepole longevity favor establishment of more shade tolerant species and less likelihood that lodgepole pine will maintain membership by gap phase replacement.

These autecological characteristics provide a wide ecological amplitude for lodgepole pine. The species encroaches sand dunes (Kumler 1969), sagebrush steppes (Patten 1963, 1969), subalpine meadows grasslands (Dunwiddle 1977, Vale 1978), and as a successional species following burning or stand harvest, and at least a persistent seral or climax species on xeric soil parent materials or slope aspects, flat to concave basins and plateaus, or imperfectly drained profiles across much of its geographic range.

LODGEPOLE PINE CLASSIFICATION

A compilation of classification literature published since 1973 (Table 1) indicated lodgepole has been described as a seral species within 114 associations and 15 potentially different tree series. The species can be viewed as a persistent seral member in another 21 community types and as a climax species in 33 associations (Table 2 and 3).

Table 2.–Summary of plant communities in which lodgepole pine is considered a climax species.

SERIES	**PLANT COMMUNITY**	**REFERENCE**
Pinus contorta		
	Calamagrostis canadensis	Henderson *et al.* 1977
	Stipa occidentalis	Volland 1982
	Stipa occidentalis–Carex pensylvanica	Zeigler 1978; Volland 1982
	Lupinus albicaulis–Carex pensylvanica	Zeigler 1978; Volland 1982
	Poa nervosa	Henderson *et al.* 1977
	Carex rossii	Mauk & Henderson 1984
	Carex rossii–Lupinus caudatus	Volland 1982
	Danthonia californica	Dealy 1971
	Festuca idahoensis	Hopkins 1979b; Steele *et al.* 1981
	Linnaea borealis	Roberts 1980
	Forb	Hopkins 1979a
	Berberis repens	Henderson *et al.* 1977
	Shepherdia canadensis	Hoffman & Alexander 1980
	Juniperus communis	Roberts 1980
	Arctostaphylos uva-ursi	Youngberg & Dahms 1970; Pfister 1972; Hoffman & Alexander 1976; Volland 1982; Mauk & Henderson 1984
	Vaccinium scoparium	Hall 1973; Hoffman & Alexander 1976; Hopkins 1979a; Volland 1982
	Vaccinium scoparium/Carex pensylvanica	Hopkins 1979a
	Vaccinium scoparium/Calamagrostis rubescens	Hall 1973
	Vaccinium caespitosum–V. occidentalis	Volland 1982; Henderson *et al.* 1977
	Purshia tridentata	Cooper 1975; Pfister *et al.* 1977; Volland 1982
	Purshia tridentata/Festuca idahoensis	Youngberg & Dahms 1970; Volland 1982
	Purshia tridentata/Stipa occidentalis	Youngberg & Dahms 1970; Volland 1982
	Purshia tridentata/Carex pensylvanica	Youngberg & Dahms 1970; Zeigler 1978; Volland 1982
	Purshia tridentata-Ribes cereum	Youngberg & Dahms 1970; Volland 1982
	Artemisia tridentata	Volland 1982
	Artemisia tridentata/Festuca idahoensis	Volland 1982
	Arctostaphylos patula–A. nevadensis	Volland 1982
Pinus albicaulis		
	Vaccinium scoparium	Pfister *et al.* 1977; Steele *et al.* 1983
	Juniperus communis	Steele *et al.* 1983
	Carex geyeri	Steele *et al.* 1983
	Carex rossii	Steele *et al.* 1983
	Arenaria kingii	Hopkins 1979b
Pinus flexilis		
	Juniperus communis	Steele *et al.* 1983

Table 3.–Summary of plant communities in which lodgepole pine is considered a seral species. (Status A is association, status CT is community type.)

SERIES	COMMUNITY	STATUS	REFERENCE
Abies lasiocarpa			
	/ Acer glabrum	(A)	Steele *et al.* 1983; Mauk & Henderson 1984
	/ Alnus sinuata	(A)	Pfister *et al.* 1977
	/ Juniperus communis	(A)	Steele *et al.* 1981, 1983; Mauk & Henderson 1984
	/ Menziesia ferruginea	(A)	Pfister *et al.* 1977; Steele *et al.* 1981; Cooper *et al.* 1983
	/ Pachistima mysinities	(A)	Williams & Lillybridge 1983
	/ Phyllodoce empetriformis	(A)	Williams & Lillybridge 1983
	/ Ribes montigenum	(A)	Henderson *et al.* 1977; Steele *et al.* 1983; Mauk & Henderson 1984
	/ Rhododendron alibiflorum	(A)	Williams & Lillybridge 1983; Henderson & Peter 1983
	/ Shepherdia canadensis	(A)	Hoffman & Alexander 1976
	/ Spiraea betulifolia	(A)	Steele *et al.* 1981, 1983
	/ Symphoricarpos albus	(A)	Steele *et al.* 1983
	/ Vaccinium caespitosum	(A)	Pfister *et al.* 1977; Henderson *et al.* 1977; Steel *et al.* 1981; Williams & Lillybridge 1983; Mauk & Henderson 1984
	/ Vaccinium globulare	(A)	Pfister *et al.* 1977; Steele *et al.* 1981, 1983; Mauk & Henderson 1984
	/ Vaccinium membranaceum	(A)	Henderson *et al.* 1976
	/ Vaccinium scoparium	(A)	Hall 1973; Henderson *et al.* 1977, 1976; Pfister *et al.* 1977; Steele *et al.* 1981, 1983; Hoffman & Alexander 1983, 1980, 1976; Williams & Lillybridge 1983; Mauk & Henderson 1984
	/ Vaccinium scoparium/ Calamagrostis rubescens	(A)	Williams & Lillybridge 1983
	/ Calamagrostis canadensis	(A)	Pfister *et al.* 1977; Henderson *et al.* 1977; Cooper *et al.* 1981, 1983; Steele *et al.* 1981, 1983; Mauk & Henderson 1984
	/ Calamagrostis rubescens	(A)	Henderson *et al.* 1976; Pfister *et al.* 1977; Steele *et al.* 1981, 1983; Williams & Lillybridge 1983; Mauk & Henderson 1984
	/ Carex geyeri	(A)	Henderson *et al.* 1976; Pfister *et al.* 1977; Hoffman & Alexander 1983, 1980; Steele *et al.* 1981
	/ Carex rossii	(A)	Steele *et al.* 1983
	/ Luzula hitchcockii	(A)	Pfister *et al.* 1977; Steele *et al.* 1981
	/ Poa nervosa	(A)	Henderson *et al.* 1977
	/ Actaea rubra	(A)	Steele *et al.* 1983
	/ Arnica cordifolia	(A)	Henderson *et al.* 1976; Hoffman & Alexander 1976; Pfister *et al.* 1977; Steele *et al.* 1981, 1983
	/ Arnica latifolia	(A)	Steele *et al.* 1983
Abies lasiocarpa			
	/ Berberis repens		Henderson *et al.* 1977, 1976; Steele *et al.* 1983; Mauk & Henderson 1984
	/ Caltha leptosepala	(A)	Henderson *et al.* 1977
	/ Clematis pseudoalpina	(A)	Pfister *et al.* 1977
	/ Clintonia uniflora	(A)	Pfister *et al.* 1977; Steele *et al.* 1981; Cooper *et al.* 1983
	/ Coptis occidentalis	(A)	Cooper*et al.* 1983
	/ Galium triflorum	(A)	Pfister *et al.* 1977
	/ Linnaea borealis	(A)	Pfister *et al.* 1977; Steele *et al.* 1981, 1983; Williams & Lillybridge 1983
	/ Lupinus latifolius	(A)	Henderson & Peter 1983
	/ Osmorhiza chilensis	(A)	Henderson *et al.* 1976; Steele *et al.* 1983
	/ Pedicularis racemosa	(A)	Henderson *et al.* 1976; Schimpf *et al.* 1980; Steele *et al.* 1983; Mauk & Henderson 1984
	/ Streptopus amplexifolius	(A)	Henderson *et al.* 1977; Steele*et al.* 1981; Mauk & Henderson 1984
	/ Thalictrum occidentale	(A)	Steele *et al.* 1983
	/ Xerophyllum tenax	(A)	Pfister *et al.* 1977; Steele *et al.* 1981; Cooper *et al.* 1983
Picea engelmannii			
	/ Juniperus communis	(A)	Steele *et al.* 1983
	/ Physocarpus malvaceus	(A)	Pfister *et al.* 1977
	/ Ribes montigenum	(A)	Steele *et al.* 1983
	/ Vaccinium caespitosum	(A)	Pfister *et al.* 1977; Henderson *et al.* 1977; Mauk & Henderson 1984
	/ Vaccinium scoparium	(A)	Hoffman & Alexander 1976; Henderson *et al.* 1977; Steele *et al.* 1983; Mauk & Henderson 1984
	/ Carex disperma	(A)	Steele *et al.* 1981
	/ Arnica cordifolia	(A)	Steele *et al.* 1983
	/ Caltha leptosepala	(A)	Henderson *et al.* 1977; Steele *et al.* 1983; Mauk & Henderson 1984
	/ Clinton uniflora	(A)	Pfister *et al.* 1977
	/ Equisetum arvense	(A)	Steele *et al.* 1983; Mark & Henderson 1984

Table 3.—Continued

SERIES	COMMUNITY	STATUS	REFERENCE
	/ Galium triflorum	(A)	Pfister *et al.* 1977; Steele *et al.* 1983, 1984
	/ Linnaea borealis	(A)	Pfister *et al.* 1977; Steele *et al.* 1983
	/ Smilacina stellata	(A)	Pfister *et al.* 1977
Tsuga mertensiana			
	/ Menziesia ferruginea	(A)	Pfister *et al.* 1977; Cooper *et al.* 1983, 1982; Volland 1982
	/ Vaccinium membranaceum/ Xerophyllum tenax	(A)	Hemstrom *et al.* 1982
	/ Vaccinium scoparium	(A)	Zeigler 1978; Hopkins 1979; Hemstrom *et al.* 1982; Volland 1982
	/ Luzula hitchcockii	(A)	Pfister *et al.* 1977
	/ Clintonia unifolia	(A)	Cooper *et al.* 1983; Volland 1982
Abies amabilis			
	/ Rhododendron marcrophyllum/ Xerophyllum tenax	(A)	Hemstrom *et al.* 1982
	/ Rubus lasiococcus	(A)	Williams 1978
	/ Vaccinium membranaceum/ Xerophyllum tenax	(A)	Hemstrom *et al.* 1982
Tsuga heterophylla			
	/ Clintonia unifolia	(A)	Pfister *et al.* 1977; Cooper *et al.* 1983
Abies magnifica var. shastenis			
	/ Arctostaphlos nevadensis/ Carex pensylvanica	(A)	Zeigler 1978; Hopkins 1979a; Volland 1982
	/ Chimaphila umbellata	(A)	NcNeil 1976
	/ Carex pensylvanica	(A)	Hopkins 1979a
	/ Carex pensylvanica-Lupinus albicaulis	(A)	Zeigler 1978
Abies concolor			
	/ Ceanothus velutinus-Arctostaphylos patula	(A)	Volland 1982
	/ Ceanothus velutinus	(A)	Volland 1982
	/ Ceanothus velutinus/Carex pensylvanica	(A)	Volland 1982
	/ Chimaphila umbellata	(A)	McNeil 1976
	/ Symphoricarpus albus/ Stellaria jamesiana	(A)	Hopkins 1979b
	/ Carex pensylvanica-Penstemon euglaucus	(A)	Volland 1982
	/ Carex pensylvanica-Stipa occidentalis	(A)	Hopkins 1979b
	/ Berberis repens	(A)	Henderson *et al.* 1977
Calocedrus decurrens			
	/ Arctostaphylos patula	(A)	Zeigler 1978
Picea pungens			
	/ Berberis repens		Henderson *et al.* 1977; Mauk & Henderson 1984
Abies grandis			
	/ Pachistima myrsinites	(A)	Williams 1978
	/ Physocarpus malvaceus	(A)	Cooper *et al.* 1983
	/ Vaccinium caespitosum	(A)	Pfister *et al.* 1977; Steele *et al.* 1981
	/ Vaccinium globulare	(A)	Steele *et al.* 1981, 1983
	/ Vaccinium membranaceum	(A)	Hall 1973; Johnson 1981
	/ Vaccinium scoparium	(A)	Hall 1973
	/ Calamagrostis rubescens	(A)	Steele *et al.* 1981
	/ Clintonia uniflora	(A)	Pfister *et al.* 1977; Steele *et al.* 1981; Cooper *et al.* 1983
	/ Coptis occidentalis	(A)	Cooper *et al.* 1983
	/ Linnaea borealis	(A)	Hall 1973; Pfister *et al.* 1977; Steele *et al.* 1981; Johnson 1981; Cooper *et al.* 1983
	/ Pyrola secunda	(A)	Williams 1978
	/ Xerophyllum tenax	(A)	Pfister *et al.* 1977; Cooper *et al.* 1983
Pseudotsuga menziesii			
	/ Acer glabrum	(A)	Steele *et al.* 1983
	/ Arctostaphylos uva-ursi	(A)	Williams & Lillybridge 1983; Henderson & Peter 1983
	/ Cornus canadensis	(A)	Roberts 1980
	/ Juniperus communis	(A)	Pfister *et al.* 1977; Steele *et al.* 1981, 1983
	/ Physocarpus malvaceus	(A)	Pfister *et al.* 1977; Mauk & Henderson 1984
	/ Physocarpus monogynus	(A)	Hoffman & Alexander 1976
	/ Spiraea betulifolia	(A)	Steele *et al.* 1981, 1983
	/ Symphoricarpos albus	(A)	Pfister *et al.* 1977; Steele *et al.* 1981, 1983

Table 3.–Continued

SERIES	COMMUNITY	STATUS	REFERENCE
	/ Vaccinium caespitosum	(A)	Cooper *et al.* 1983; Williams & Lillybridge 1983
	/ Vaccinium globulare	(A)	Pfister *et al.* 1977; Cooper *et al.* 1983
	/ Calamagrostis rubescens	(A)	Pfister *et al.* 1977; Steele *et al.* 1981, 1983; Johnson 1981; Williams & Lillybridge 1983; Mauk & Henderson 1984
	/ Carex geyeri	(A)	Steele *et al.* 1981
	/ Arnica cordifolia	(A)	Steele *et al.* 1981, 1983
	/ Berberis repens	(A)	Hoffman & Alexander 1976; Henderson *et al.* 1977; Steele *et al.* 1983; Mauk & Henderson 1984
	/ Linnaea borealis	(A)	Pfister *et al.* 1977
	/ Osmorhiza chilensis	(A)	Steele *et al.* 1983; Mauk & Henderson 1984
Pinus ponderosa			
	/ Purshia tridentata/ Festuca idahoensis	(A)	Volland 1982
	/ Purshia tridentata/ Stipa occidentalis	(A)	Volland 1982
	/ Purshia tridentata/ Carex pensylvanica	(A)	Volland 1982
	/ Purshia tridentata-Ceanothus velutinus/Carex pensylvanica	(A)	Volland 1982
	/ Arctostaphylos patula/Festuca idahoensis	(A)	Henderson *et al.* 1977; Mauk & Henderson 1984
Pinus contorta			
	/ Juniperus communis	(CT)	Steele *et al.* 1983; Mauk & Henderson 1984
	/ Shepherdia canadensis	(CT)	Steele *et al.* 1983
	/ Spiraea betulifolia	(CT)	Steele *et al.* 1983
	/ Vaccinium caespitosum	(CT)	Pfister *et al.* 1977; Henderson *et al.* 1977; Steele *et al.* 1981; Cooper *et al.* 1983
	/ Vaccinium globulare	(CT)	Steele *et al.* 1983
	/ Vaccinium membranceum	(CT)	Hall 1973; Johnson 1981
	/ Vaccinium scoparium	(CT)	Hall 1973; Hoffman & Alexander 1976; Henderson *et al.* 1977; Pfister *et al.* 1977; Steele *et al.* 1981, 1983; Volland 1982; Cooper *et al.* 1983; Mauk & Henderson 1984
	/ Calamagrostis rubescens	(CT)	Cooper 1975; Pfister *et al.* 1977; Steele *et al.* 1983
	/ Calamagrostis canadensis	(CT) (A)	Henderson *et al.* 1977; Mauk & Henderson 1984
	/ Carex geyeri	(CT)	Steele *et al.* 1981; 1983
	/ Carex rossii	(CT)	Steele *et al.* 1983
	/ Sitanion hytrix-Carex pensylvanica	(CT)	Hopkins 1979b
	/ Stipa occidentalis-Lupinus caudatus-Linanthastrum nuttallii	(CT)	Volland 1982
	/ Arnica cordifolia	(CT)	Steele *et al.* 1983
	/ Berberis repens	(CT) (A)	Henderson *et al.* 1977; Mauk & Henderson 1984
	/ Caltha leptosepala	(CT)	Henderson *et al.* 1977
	/ Linnaea borealis	(CT)	Pfister *et al.* 1977; Steele *et al.* 1983
	/ Xerophyllum tenax	(CT)	Volland 1982; Cooper *et al.* 1983
Populus tremuloides			
	/ Thalictrum fendleri	(A)	Hoffman & Alexander 1980
	/ Equisetum arvense	(CT)	Youngblood & Mueggler 1981
	/ Prunus virginiana	(CT)	Youngblood & Mueggler 1981
Populus tremuloides-Abies lasiocarpa			
	/ Arnica cordifolia	(CT)	Youngblood & Mueggler 1981
Populus tremuloide-Pinus contorta			
	/ Calamagrostis rubescens	(A)	Mueggler & Campbell, Jr. 1982
Populus tremuloides-Pseudotsuga menziesii			
	/ Calamagrostis rubescens	(A)	Mueggler & Campbell, Jr. 1982
	/ Symphoricarpos oreophilus	(A)	Mueggler & Campbell, Jr. 1982

SUCCESSIONAL RELATIONSHIPS OF LODGEPOLE PINE

Stands in which lodgepole pine is described as seral occur where the environment will permit establishment and growth of other species. The environment may need to be modified by initial establishment of lodgepole for other species to colonize the site. The successional relationship of lodgepole pine to other species has been interpreted from stand dynamics following fire, species longevity, and species regeneration characteristics. Critical to the persistence of lodgepole in a stand is whether mature individuals will live long enough to maintain at least codominance with other species by the time of disturbance (Cattelino *et al.* 1979). Absence of significant stand disturbance within the physiological age of lodgepole will favor regeneration and eventual dominance of shade tolerant species on sites where they can establish and grow. These stands are most often interpreted as those in which lodgepole pine is successional to other species. Population studies which evaluate size or age distributions (Knowles and Grant, 1983), together with documentation of stand history, is the most efficient approach to evaluating the successional status of the species.

Equally important is the frequency of disturbance. Lodgepole pine could be significantly reduced in a stand by the recurrence of disturbance at frequencies less than 15 to 20 years (Cattelino *et al.*, 1979). Underburning or precommercial thinning are the two disturbance agents that would provide this frequency. Given even-aged stands without a seedbearing overstory, the species rarely produces enough seed to regenerate favorable seedbeds prior to this age.

The success of lodgepole pine to regenerate following disturbance is strongly controlled by the persistence of a seed source and the size of the area disturbed. Often stand replacement occurs as a gap phase process leading to even-aged small groups of lodgepole in an uneven-aged matrix of other species including lodgepole. Under gap phase replacement, the disturbance is very localized and adjacent individuals may provide the seed source. Larger areas of disturbance, as occurs from catastrophic fire or extensive clearcutting, require either a serotinous cone habit, or a scattered residual overstory and proper timing of harvest in the case of nonserotiny.

The species has been cited (Table 1) as seral to Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*) to Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*) and grand fir (*Abis grandis*) in addition to western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), mountain hemlock (*Tsuga mertensiana*), whitebark pine (*Pinus albicaulis*), ponderosa pine (*Pinus ponderosa*) and white fir (*Abies concolor*) as a result of fire or logging. Lodgepole pine has successfully established within 10 to 20 years after fire even though cone serotiny is infrequent over portions of its range. In the absence of burning or stand harvest with site preparation, lodgepole pine fails to regenerate in the shade of competitors and reaches its physiological rotation within 200-300 years, and other species become overstory dominants within 120 to 200 years. Fire intervals less than 100 to 150 years were found to favor lodgepole dominance, intervals exceeding 200 years could eliminate the species from stands since it fails to regenerate in the shade of competitors (Loope and Gruell 1973, Whipple and Dix 1979, Antos and Habeck 1981, Arno 1981, Romme and Knight 1981, Romme 1982, Fischer and Clayton 1983).

One agent that may hasten stand conversion to more tolerant species is the mountain pine beetle (*Dendroctonus ponderosae*) which select the larger lodgepole stems. The residual lodgepole and its competitors are released by the infestation and grow 20 to 40 years to a size in which lodgepole is again conducive to beetle attack (Amman 1977). Eventually lodgepole pine is eliminated from the stand by lack of recruitment and differential harvesting of larger stems. On sites considered marginal for regeneration of competitors, windthrow of beetle-killed overstory provides microsites receptive to lodgepole seedling establishment and may slow competitor dominance by several hundred years. Lodgepole may appear as a persistent seral species under these conditions.

LODGEPOLE PINE AS A PERSISTENT SERAL SPECIES

From a pragmatic viewpoint lodgepole pine can be classified as a persistent seral species in many stands in which it is considered as successional. Periodic disturbance as from windthrow, beetle mortality, controlled light underburning and stand harvest, may perpetuate lodgepole in the plant community.

Romme and Knight (1981) describe lodgepole pine as being a persistent seral species in southwestern Wyoming (Medicine Bow Mts.) where natural fire is infrequent but recurs before the more shade-tolerant spruce and subalpine fir can replace lodgepole. Romme (1982) considered lodgepole pine as a persistent stand component in Yellowstone Park even after 250-300 years, because of gap phase replacement attributed to mountain pine beetle mortality. The replacement fire cycle in the Park was thought to be around 300-400 years, because fuel accumulation reaches a maximum and understory ladder fuels will support an intense crown fire by this time. The cyclic nature of this ecosystem led Romme to question the existence of a steady-state where cyclic changes in stand structure and function occur as a result of periodic, large destructive fires. Antos and Habeck (1981) describe lodgepole as a persistent seral species in the intermountain valleys of northwestern Montana when disturbance frequency is less than about 160 years.

These environments supporting "persistent" lodgepole are usually marginally suited for establishment of competitor species. Establishment or subsequent growth proceeds very slowly so that overstory dominance by these competitors rarely occurs before some disturbance factor provides an environment suitable for lodgepole regeneration. Stands on harsh environments (too xeric, cold or wet) will probably be a mixture of lodgepole pine with other species, even in their more advanced development. Efforts to remove lodgepole from the stand will not be cost-effective or successful toward truncating the regeneration process. Under these conditions the manager must accept lodgepole as a significant component of the stand. Lodgepole in these situations is classed as a dominant or persistent seral by some ecologists (Pfister and Daubenmire 1975).

CLIMAX RELATIONSHIPS OF LODGEPOLE PINE

Literature published over the last 10-15 years indicates there are situations where lodgepole pine can be considered as climax, i.e. self-regenerating under the prevailing microclimate and edaphic environment. These situations have been described by Pfister *et al.* (1977) as (1) repeated conflagration or light underburning eliminates seed sources of potential competitors, (2) absence of catastrophic disturbances permits development of dense lodgepole stands which prevent any conifer regeneration until stand deterioration, and (3) sites having environmental characteristics which are too harsh for establishment of other species.

Moir (1969) described climax or persistent lodgepole pine in Colorado as growing on gentle slopes and coarse-textured granites between 2500 and 2800 meters (8200-9300 feet). These stands originated from wildfire and were restocked within 10 years of the burn. Lodgepole regeneration is occurring by gap phase replacement into holes created in the tree overstory. Often these openings are created by beetle mortality in the larger stems. A bimodal diameter distribution results. No significant regeneration of spruce, subalpine fir or Douglas-fir occurs after 65 to 100 years since the sites are thought to be warmer and drier than required for these species. Most seedling mortality of competitors occurs during the first growing season even within the overstory protection of lodgepole.

Romme (1982) described a climax lodgepole pine/elk sedge (*Carex geyeri*) association in Yellowstone National Park. Initial tree establishment in the association may span over 30 years as a result of summer drought mortality, herbaceous competition or inadequate seed source. Extensive overstory mortality occurs between 250 and 300 years with enough fuel accumulated to support a crown fire every 300 to 400 years. A more recent study by Despain (1983) further substantiates Romme's observations that lodgepole pine forms a stable community in the absence of replacement fires in Yellowstone Park. The size class distribution was found to fit an inverse J-shaped curve typical of self-regenerating stands.

Lodgepole has such a broad ecological amplitude it can dominate in environments where regeneration of associated species has difficulty either establishing or growing. Climax lodgepole can be found on cold topographic slope positions, associated with seasonally high water tables, geologically young parent materials or xeric soil profiles.

Youngberg and Dyrness (1959) described climax lodgepole in central Oregon as occurring on well-drained coarse pumice soils, areas with seasonally high water tables, and lower slope positions which accumulate cold air. These pumice soils are very porous, and consequently, conduct heat poorly (Cochran *et al.* 1967). The soil surface is exceptionally hot during a summer midday and readily loses surface heat overnight. Seedling losses in this environment are often attributed to either drought or heat injury during the summer months (Cochran 1975, 1973). Stephens (1966) also documents climax lodgepole pine being associated with droughty, sandy soils of low fertility in the Mt. Hood area, northcentral Oregon.

Low air temperatures and cold air ponding also influence seedling mortality and the distribution of species. Cochran and Bernsten (1973) have shown that lodgepole pine seedlings could tolerate lower night temperatures at the seedling emergence period than ponderosa pine. Ponderosa pine may be eliminated from frost pocket areas in central Oregon due to its susceptibility to cold temperatures in the seedling emergence stage. The flowering structures of these two species also show the same differential frost tolerance (Sorensen and Miles 1974). Cold environments at higher elevations have been given as reason for climax lodgepole pine in the northern Rocky Mountains (Pfister *et al.* 1977). Rehfeldt (1980) indicates that lodgepole is more cold tolerant than Douglas-fir and that the susceptibility of lodgepole to freezing will vary with the geographic population.

The tolerance of lodgepole pine to high water tables has been documented by Cochran (1972) and Minore (1970). Water table, however, has not been separated as the sole cause for lodgepole pine occupying wet sites. The high incidence of pocket gopher activity in mesic lodgepole pine associations of central Oregon provides a level of soil disturbance that is also conducive to reestablishment of lodgepole pine (Volland 1974).

An investigation of the Big Horn Mountains in Wyoming by Despain (1973) indicates lodgepole pine, while being seral to Engelmann spruce and subalpine fir at mesic upper elevations and to Douglas-fir at lower elevations on sedimentary soils, also occurs as climax stands on predominately granitic soils.

A study in the Wind River Mountains of Wyoming by Reed (1976) described climax lodgepole occurring in a belt between 2400 and 2900 meters elevation (7875-9500 feet) with Douglas-fir predominantly downslope and spruce-fir at higher elevations similar to that described by Moir (1969) and Despain (1973). Lodgepole was considered seral in the subalpine fir/Wheeler bluegrass (*Poa nervosa*) association as a result of burning or logging. The lodgepole pine/Wheeler bluegrass association was considered persistent within the same elevation belt since no other tree species was successfully replacing lodgepole pine. The association was prominent toward the southern end of Wind River Mts. where environments are drier and less fertile (lower cation exchange capacity and base saturation) on schist-derived soils.

A successional study within the Fraser Experimental Forest, Colorado Front Range by Whipple and Dix (1979) indicated lodgepole as stable or climax on the driest topographic positions between 2850 and 3000 meter (9350-9480 feet). Lodgepole has a bimodal age distribution indicating the species was self-perpetuating by gap phase replacement. The sample stands were over 250 years old with no indication of replacement by other species. Replacement of lodgepole by spruce and subalpine fir usually requires up to 100 years in this area given an available seed source and absence of a fire. Fire was not considered a necessary requirement for reestablishment of lodgepole in these stands. The authors considered the inability of spruce or fir to establish under a lodgepole pine overstory as reason enough to designate a lodgepole pine climax.

LODGEPOLE PINE CLASSIFICATION AND RESOURCE MANAGEMENT

It is important to realize that lodgepole pine can function over much of its geographical range as either a climax or seral species depending upon stand history and inherent environmental characteristics. The management of stands containing lodgepole pine is strongly influenced by the successional status of the species on that particular site. Ecological classifications will usually state or imply the successional status of lodgepole pine. The forester should determine these successional relationships early in the prescription phase of stand treatment. A stratification of lodgepole pine stands into seral, persistent seral or climax helps (1) identify important interactions between stand components, (2) provides information about changes in composition and structure in a spacial and temporal dimension, and (3) permits an allocation of management effort to those sites where either resource values or risk of stand deterioration or opportunities for species manipulation are the greatest.

Stands in which lodgepole pine occurs as either a seral or persistent seral member provide the greatest challenge for silvicultural treatment. The presence of an onsite seed source in the form of serotinous cones on slash or scattered residual trees greatly increases the probability that lodgepole will be a significant component of the second generation stand. Often site preparation techniques such as underburning, slash piling, and strip scarification provide the environment conducive to lodgepole reestablishment. Preferential treatments to discourage lodgepole are most effective early in the life of a stand. Stands composed of fire tolerant species such as Douglas-fir, western larch or ponderosa pine can be underburned to select against the more susceptible lodgepole. A more predictable approach is to remove lodgepole with a precommercial thinning timed for the conebearing age of the species. A wood fiber management objective might hold lodgepole in the stand until a commercial thinning is used to weed the species from a mix of other species on longer rotations. Where economic or yield objectives dictate short rotations, the practical solution is to either manage for lodgepole as the stand dominant or accept a species mix.

Seral stands have significant implications for aesthetics and wilderness management. Fire management policies should recognize the cyclic nature of lodgepole stand development. Effective control of fire will change stand structure to more mesic, or shade tolerant species. An effort to reduce the probability of a conflagration fire will require a more active management of several low intensity burns.

Climax lodgepole pine communities serve as significant management indicators. Attempted introductions of other tree species usually results in failure at the regeneration stage. The reason for a stable lodgepole ecosystem should be outlined so the probable factors limiting tree establishment can be identified. Planting cold intolerant species into flatter topographic positions or species requiring good soil aeration into imperfectly-drained sites serve as an example.

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ECOLOGICAL CLASSIFICATION OF LODGEPOLE PINE IN CANADA

Jim Pojar

ABSTRACT

The most pervasive ecological classification within the Canadian range of lodgepole pine is a biogeoclimatic ecosystem classification adapted by the Alberta and British Columbia Forest Services from the pioneering work of V. J. Krajina and his students. The taxa result from a synthesis of climate, vegetation, and soil data. The system includes ecosystem units (associations, subassociations, types), which are synthesized from individual ecosystems or biogeocoenoses, and biogeoclimatic units (zones, subzones, variants), which represent geographical areas. Zonal or climatic climax associations characterize subzones, and provide the link between the two types of units.

British Columbia and Alberta are presently divided into 17 or 18 biogeoclimatic zones and numerous subzones. Lodgepole pine occurs in all but three of these zones, but is most abundant in cool, montane and subalpine, interior portions of the Canadian Cordillera. Lodgepole pine functions as a possible climatic climax species in only one area, a cold, dry subzone in the Chilcotin district of B.C. Although traditionally viewed as a seral species, lodgepole pine could be interpreted as a major component of "climax" vegetation where frequent, large-scale disturbance is normal.

The classification of one subzone of the Sub-Boreal Spruce Zone is outlined at the ecosystem level. Floristic and habitat features are summarized for three of the ten forest associations that have been differentiated in the subzone. Silvicultural interpretations linked to the classification involve reforestation, tree species selection, site preparation, brush hazard, stock type, stocking standards, and density control. Aids to ecosystem identification and interpretation include maps, descriptions, keys, habitat grids, topographic sequences, guides to plant identification, outlines of management recommendations, and an active training program.

Future research needs include completion of the initial classification; classification of seral ecosystems; studies on succession, energy and biogeochemical cycling, site productivity, and impacts of management on these processes; and a system of ecological reserves.

INTRODUCTION

Lodgepole pine (*Pinus contorta*) ranges through most of the Canadian Cordillera from the Canada-United States border up into the southern Yukon. Several different systems of ecological classification are used within this area. In southern British Columbia, a limited amount of habitat type classification (Daubenmire 1968; Pfister and Arno 1980) has been done by McLean (1970), Packee (1976), and Beese (1981). Biophysical land classification (Lacate 1969; Walmsley and van Barneveld 1977) has been practiced fairly widely in B.C. (*e.g.*, Vold *et al.* 1980), western Alberta (*e.g.*, Holland *et al.* 1976), and southern Yukon (Stanek 1980). Related, more general ecoregion classifications have been developed for Alberta (Strong and Leggat 1981) and the Yukon (Oswald and Senyk 1977). However, the most pervasive system is the biogeoclimatic ecosystem classification developed by Krajina (1965, 1969) and his students, and subsequently adapted by the B.C. and Alberta Forest Services and several forest companies. This classification has been applied over most of B.C. (Pojar 1983) and much of western Alberta (Kojima 1980; Corns and Annas[1]).

Biogeoclimatic ecosystem classification is a classification of ecosystems (also called biogeocoenoses). The taxa result from a synthesis of climate, vegetation, and soil data. The classification is being developed as a multi-level hierarchy with two primary sections or areas of emphasis: ecosystem levels of integration, and biogeoclimatic or zonal levels (fig. 1). Each section has several heirarchical taxonomic categories, as explained below.

CONCEPTS

Ecosystem and Biogeocoenose

Ecosystem is the term used for the sum total of vegetation, animals, and physical environment in whatever size segment of the world is chosen for study (Fosberg 1967). A biogeocoenose (in the sense of Sukachev and Dylis 1964) is a special case of the ecosystem, but we use the two terms interchangeably. For our purposes, a terrestrial ecosystem (biogeocoenose) may be practically characterized by a plant community (an area of relatively uniform vegetation) and the soil polypedon (an area, to the effective depth of the solum, or relatively uniform soil) upon which the plant community occurs.

Zonal Ecosystem

Zonal or climatic climax ecosystems are those in which the integrated influence of climate on vegetation, soil, and other ecosystem components is most strongly expressed. Such ecosystems generally are considered to develop on gentle to

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[1] Corns, I. G. W., and R. M. Annas. 1983. Ecological classification of Alberta forests and its application for forest management. Paper presented at Aug. 14-17, 1983 meeting of International Committee on High Latitude Silviculture. Fairbanks, Alaska. USA.

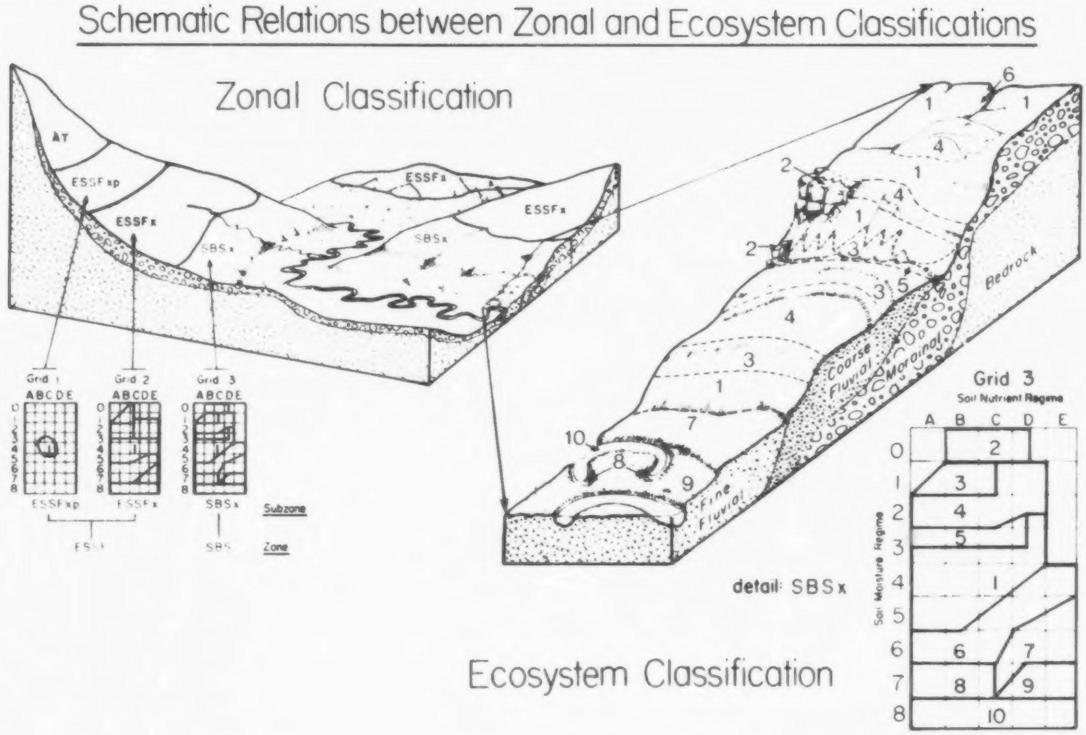
Schematic Relations between Zonal and Ecosystem Classifications
Zonal Classification
AT
ESSFxp
ESSFx
ESSFx
ESSFx
SBSx
SBSx
Grid 1
Grid 2
Grid 3
ABCDE
0
1
2
3
4
5
6
7
8
ESSFxp
ESSFx
SBSx
Subzone
ESSF
SBS
Zone
6
1
1
4
2
4
1
1
2
3
3
5
4
3
1
7
10
8
9
Coarse Fluvial
Morainal
Bedrock
Fine Fluvial
detail: SBSx
Grid 3
Soil Nutrient Regime
A B C D E
Soil Moisture Regime
0
1
2
3
4
5
6
7
8
2
3
4
5
1
6
7
8
9
10
Ecosystem Classification

Figure 1. – Schematic relations between zonal and ecosystem sections of classification. AT = Alpine Tundra Zone; ESSFx and ESSFxp = hypothetical forested and parkland subzones, respectively, of the Engelmann Spruce – Sub-alpine Fir Zone; SBSx = a hypothetical subzone of the Sub-Boreal Spruce Zone.

moderate slopes, on deep, loamy, moderately well drained soils that have average or intermediate moisture and nutrient status (see Sukachev and Dylis 1964: 441; Daubenmire 1968: 229, 1978: 320-321; Walter 1973: 27).

These attributes result in biogeochemical cycling, energy exchange, and biomass development that are more or less independent of local relief and soil parent material, and are in equilibrium with the regional climate. Hence, zonal ecosystems are used to characterize and delineate biogeoclimatic units.

Climax and Succession

According to what has been termed the traditional view (Drury and Nisbet 1973), ecosystems arrive at climax through a process of change called ecological succession, the progressive development of ecosystems through time. In theory, succession ends in a mature, climax ecosystem of relatively stable species composition and steady-state function, adapted to its environment and essentially permanent if undisturbed (Daubenmire 1968; Odum 1969; Whittaker 1975).

Climax and succession in British Columbia and western Alberta

The concepts of climax and succession have generated considerable controversy, much of it revolving around definitions, distinguishing criteria, structural and functional attributes, and the reality of both the climax state and the successional process. We generally follow the traditional view of climax and succession and, although many ecologists dispute this view, it provides useful insights and part of the conceptual basis of our classification.

Many forest ecosystems in northwestern North America escape large-scale catastrophic destruction by fire, wind, and other agents (Brady and Hanley[1]; Parminter 1983). Succession may continue over several centuries (Harris and Farr 1974;

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[1] Brady, W. W., and T. A. Hanley. 1982. The role of disturbance in old-growth forests of southeast Alaska: some theoretical implications. Paper presented at Symposium: Old-Growth Forest – Wildlife Relationships. Juneau, Alaska, USA.

Waring and Franklin 1979; Alaback 1982; Henderson 1982), and large tracts of old forest occur throughout the region. These forests can be termed old (most exceed 200 years in age), old-growth (in the sense of Franklin *et al.* 1981), uneven- or multi-aged, climax, decadent, over-mature, steady state, or dynamic equilibrium, depending on actual stand structure and one's perspective. In any case, such forests are common in the Canadian Cordillera and they dominate the landscape of the wetter parts of the region.

In contrast, many other areas of the region are dominated by ecosystems that have not attained theoretical climax, and perhaps never will. For example, theoretical-climax forests are rather imaginary entities in the boreal forest (Rowe 1961; Dix and Swan 1971; Raup and Stout 1981). The boreal forest of northern B.C. and Alberta is essentially a lightning-fire climax system (Viereck and Schandelmeir 1980; Parminter 1983), with a fire cycle or fire rotation of about 140 years (Parminter, personal communication). It appears that unidirectional development of vegetation and steady-state ecosystems do not occur (Heinselman 1981). Older stands can be found, but it would be impractical to rely on rare, relict, 200-year old stands for a classification of boreal forest ecosystems. Inasmuch as wildfire is so frequent and such an integral part of boreal ecosystems, it may be more valid to think of the whole mosaic of "seral" ecosystems as a stable but dynamic climax (cf. Rowe and Scotter 1973; Wright 1974; Larsen 1980; Heinselman 1981).

Most forests in the drier parts of central and southern B.C. and southwestern Alberta have originated in some sort of large-scale disturbance (usually fire, insect attack, or windthrow), and it is difficult to find stands that are older than 150 years. Even with modern forest protection practices, most unlogged stands will not escape disturbance for more than 100 years. In these areas, we arbitrarily designate any stand older than 125 years or so as "climax", even though such stands may contain species that cannot regenerate efficiently beneath their own canopy and would be expected to decline with time and further development towards the theoretical climax.

Furthermore, because of widespread natural and logging disturbance, and because most of our commercial forests will be managed as seral stands, we sample maturing seral (usually 70 years or older) as well as near-climax and climax stands. As with habitat type classification, the trends toward climax, rather than the theoretical climax itself, are the practical basis for classification in areas with recurrent, large-scale disturbance regimes.

Post-disturbance communities often have a general resemblance to pre-disturbance communities in such areas (Corns and La Roi 1976; Viereck and Dyrness 1979), so mature (70 plus-year old) stands should be suitable for sampling and classifying forested ecosystems. These forest communities should maintain a certain floristic integrity over long periods of disturbance-prone time, even though they do not conform to the traditional concept of climax forests. Clementsian succession and climax are not required for such a classification. Nevertheless, we refer to the traditional concepts for ease of communication and to avoid militant iconoclasm.

THE CLASSIFICATION SYSTEM

Ecosystem levels of classification

Classification at ecosystem levels involves small areas relatively homogeneous in vegetation, soils, and implicitly in patterns of nutrient and energy dynamics, whereas classification at biogeoclimatic levels involves broad geographical areas of similar climate. Table 1 summarizes the hierarchy.

The most commonly used taxonomic categories within the ecosystematic section are ecosystem association, subassociation, and type. However, phases and variations of associations and subassociations are also recognized and frequently used although the phase and variation are not formal categories in the classification.

Ecosystem type—The classification groups similar plant communities into plant associations, and similar soil polypedons into soil families. A plant association is an abstraction conceived from all communities that share a characteristic combination of species, and in which the dominant species of corresponding layers are essentially the same (Daubenmire 1968: 28-30; Mueller-Dombois and Ellenberg 1974: 173-176). A soil family is a group of soils with similarities in properties such as parent materials, texture, mineralogy, horizons, depth, humus form, and soil climate (Canada Soil Survey Committee 1978: 16,115). We define an ecosystem type as all ecosystems (land areas plus their biota) with vegetation belonging to the same climax plant association on soil of a single soil family.

Ecosystem association—We then define the association as all ecosystems with vegetation belonging to the same climax plant association. The concept of the ecosystem association is similar to that of the habitat type of Daubenmire (1968) and Pfister and Arno (1980).

Ecosystem subassociation—The subassociation is designed to recognize variation in the relative abundance of one or more important species. The vegetative differences appear to reflect trends in local climatic, edaphic or very long-term successional factors, but are not considered significant enough to warrant the recognition of a distinct association.

Ecosystem association phase—The phase is basically a functional subdivision of the ecosystem association or subassociation and recognizes contrasting soil or landform characteristics that may be important to the users of the classification. Ecosystem phases might be based on soil particle size classes, slope classes, aspect, parent materials, or bedrock geology.

Table 1.—Synopsis of ecosystematic and biogeoclimatic sections of classification.

		Ecosystematic section
Unit	Major differentiae	Example
Association	Vegetation	*Picea glauca x engelmannii - Abies Lasiocarpa - Cornus canadensis - Pleurozium schreberi - Ptilium crista - castrensis* (SBSe1/01)
Subassociation	vegetation	*Picea - Abies - Vaccinium membranaceum - Cornus - Pleurozium - Ptilium* (SBSe1/01.1)
Type	vegetation, soil	*Picea - Abies - Vaccinium - Pleurozium - Ptilium* on fine-loamy Brunisolic Gray Luvisol with Hemimor on morainal blanket (SBSe1/01.1/1)
Variation	vegetation, stand history	*Picea - Abies - Vaccinium - Cornus - Pleurozium - Ptilium, Alnus viridis* variation (SBSe1/01.1/1 (2))
(Phase)[1]	soil, landform, parent materials, topography, bedrock geology	Coarse textured phase on gravelly glacial till (SBSe1/01.1(a))
		Biogeoclimatic Section
Zone	regional climate, vegetation, soil	Sub-Boreal Spruce Zone (SBS)
Subzone	regional climate, vegetation, soil	Moist cool northern subzone (SBSe)
Variant	regional climate, vegetation, soil, physiography	Western variant (SBSe1)
(Phase)[1]	local climate,	Cold air drainage phase (SBSe1(a))

[1] Neither the ecosystem nor the biogeoclimatic phase is a formal category in the classification.

Ecosystem association variation—We use the variation to describe vegetative trends or floristic features that diverge somewhat from the central concept of the association. Usually such variability is related to short-termed successional factors and involves recent stand history. Variations might be recognized on the basis of stocking, species composition of the tree stratum, understory structure and composition, etc.

Biogeoclimatic levels of classification

The biogeoclimatic section provides higher categories in the taxonomic hierarchy to accommodate further generalization of ecosystem units, based mainly on climatic relationships. Biogeoclimatic units or categories commonly used are the zone, subzone, and variant. In addition, phases are recognized and used, but the phase is not a formal category in the classification because it reflects local rather than regional climate.

Biogeoclimatic subzone—A distinct climatic climax or zonal ecosystem association characterizes a subzone. Subzones are the basic units of biogeoclimatic classification, and are the first to be recognized in the classification process. Note that the two sections of the classification are linked through the fundamental relationship between the zonal ecosystem association and the subzone.

Biogeoclimatic variant—Variants reflect further differences in regional climate, and are generally recognized for areas that are drier, wetter, snowier, warmer, or colder than other areas in the subzone. These climatic differences result in corresponding differences in vegetation, soil, and ecosystem productivity.

Biogeoclimatic phase—The biogeoclimatic phase accommodates variation, resulting from local relief, in the regional climate of subzones and variants. Phases are useful in designating significant, extensive areas of ecosystems that are, for topographic or topoedaphic reasons, atypical for the regional climate.

Biogeoclimatic zone—We group subzones with affinities in climatic characteristics and zonal ecosystems into zones. A biogeoclimatic zone is a large geographic area with a broadly homogeneous regional climate. Consequently a zone has characteristic webs of energy flow and nutrient cycling, and typical patterns of vegetation and soil. Closely related, zonal ecosystem associations characterize zones. Zones are usually named by one or more of the dominant climax species or by the prevailing vegetation physiognomy; a geographical modifier is often added to the name.

BIOGEOCLIMATIC ECOSYSTEM CLASSIFICATION AND LODGEPOLE PINE

British Columbia and Alberta are presently divided into seventeen or eighteen biogeoclimatic zones (or their equivalents), depending on individual interpretation (*cf.* Krajina 1971, 1979; Kojima 1980; Strong and Leggat 1981; Krajina *et al.* 1982; Pojar 1983). *Pinus contorta s. lat.* occurs in all but three of these zones, the Mixed Grass and Short Grass zones of southeastern Alberta, and the Ponderosa Pine-Bunchgrass Zone of south central B.C. Table 2 presents the distribution of *Pinus contorta* and other major tree species in these zones. Lodgepole pine (*P. contorta* var. *latifolia*) is especially widespread and abundant in the Sub-Boreal Spruce (SBS) and Montane Spruce (MS) zones, and more locally abundant in the Engelmann Spruce-Subalpine Fir (ESSF), Interior Cedar-Hemlock (ICH), Aspen-Lodgepole Pine-White Spruce (ALPWS), Boreal White and Black Spruce (BWBS), and Interior Douglas-fir (IDF) zones. Shore pine (*Pinus contorta* var. *contorta*) is abundant in the Coastal Cedars-Pine-Hemlock Zone (CCPH).

Lodgepole pine probably is the most wide-spread tree species in western Alberta and B.C. It is primarily a montane and subalpine species in the southern part of its Canadian range, a lowland and montane species in central and northern B.C. and adjacent Alberta. Lodgepole pine is a consistent timberline tree only in the southwestern Cariboo/Chilcotin district of B.C., on leeward flanks of the Coast Mountains and the adjacent Camelsfoot, Marble, and Chilcotin ranges.

Consideration of the distribution of lodgepole pine among the ecosystem units of different zones provides some indication of the ecological amplitude of the species. Table 3 summarizes the ecological distribution of lodgepole pine for those zones in British Columbia in which lodgepole is a major species.

Lodgepole pine, fundamentally a shade-intolerant species (Krajina 1965; Minore 1979), functions as a possible climatic climax tree (i.e., reproducing beneath its own canopy in zonal ecosystems) in only one area in Canada—a cold, dry part of the SBS, the SBSa or Chilcotin pine subzone in the lee of the Coast Mountains (Annas and Coupé 1979; Pojar *et al.* 1984). Note that the coastal variety (shore pine) may be a climatic climax tree along the outermost northern B.C. coast, where bog woodland and slope bogs are zonal vegetation. But in most of its range, lodgepole pine is a dominant seral or persistent species, in the sense of Pfister and Daubenmire (1975). However, over much of the interior Canadian Cordillera, lodgepole pine could be interpreted as a major and often dominant component of "climatic climax" vegetation where frequent, large scale disturbance is normal (see previous discussion of climax and succession). *Pinus contorta* may occur as an edaphic climax species (either in very dry or boggy ecosystems) virtually anywhere except in most of the alpine zone and in the warmest, driest parts of the region.

In B.C., most of the 35 or so subzones in which lodgepole pine plays a major role have been at least provisionally classified into ecosystem associations. The classification and interpretation of one such subzone are outlined below as an example of the ecosystematic and interpretive aspects of the classification system.

Ecosystem Units of the SBSe, a Moist Cool Subzone of the Sub-Boreal Spruce Zone

The Sub-Boreal Spruce Biogeoclimatic Zone (SBS) occupies much of the central interior of B.C. It occurs mainly on the gently rolling terrain of the interior plateaux between 500 and 1300 m elevation.

One subzone of the SBS is the Moist cool northern subzone or SBSe. The SBSe has a continental climate characterized by seasonal extremes of temperature (mean annual temperature ca 1-2°C); severe, snowy winters; relatively low annual precipitation (500-800 mm).

We classified the forests of the western variant (SBSe1) of this subzone into ten major ecosystem associations, arranged primarily along a moisture gradient (Pojar *et al.* 1984). Table 4 summarizes key vegetational features of three of these associations, while table 5 outlines important habitat information.

Uses of the Classification

Most ecosystem classification to date has been applied to the management of timber and range resources. Management interpretations and recommendations have dealt with harvest season and method, residue management (especially slashburning), site preparation, regeneration method, species selection for logged-over or grazed areas, seedling stock type, density control, vegetation competition hazard, windthrow hazard, and silvicultural systems. The classification also provides an ideal framework for growth and yield studies, a systematic

Table 2.–Occurrence[1] of trees in the biogeoclimatic zones of Alberta and British Columbia.

Tree species	ALPWS[2]	AT[2]	AWS	BWBS	CCPH	CDF	CWH	ESSF	FGP	ICH	IDF	MS	MH	PPBG	SWB	SBS	MGP/SGP
Abies amabilis	–	–	–	–	+	–	+ + +	(+)	–	+	–	–	+ + +	–	–	–	–
A. balsamea	–	–	+	+ +	–	–	–	–	–	–	–	–	–	–	–	–	–
A. grandis	–	–	–	–	–	+ +	+	–	–	+ +	+ +	+	–	–	–	–	–
A. lasiocarpa	+	–	–	+ +	–	–	+	+ + +	–	+ +	–	+ + +	+ +	–	+ + +	+ + +	–
Acer macrophyllum	–	–	–	–	–	+ +	+ +	–	–	–	+	–	–	–	–	–	–
Alnus rubra	–	–	–	–	+ +	+ + +	+ + +	–	–	–	–	–	–	–	–	–	–
Arbutus menziesii	–	–	–	–	–	+ +	+	–	–	–	–	–	–	–	–	–	–
Betula papyrifera	+	–	+	+ +	–	+	+	–	–	+ +	+ +	+	–	+	–	+ +	–
Chamaecyparis nootkatensis	–	–	–	–	+ + +	–	+ +	(+)	–	–	–	–	+ + +	–	–	–	–
Larix laricina	–	–	+	+ +	–	–	–	–	–	–	–	–	–	–	–	(+)	–
L. lyallii	–	–	–	–	–	–	–	+ +	–	–	–	–	–	–	–	–	–
L. occidentalis	–	–	–	–	–	–	–	+	–	+ +	+ + +	+ + +	–	+	–	–	–
Picea engelmannii	(+)	–	–	–	–	–	–	+ + +	–	+ +	+	+ + +	+	–	–	–	–
P. engelmannii x glauca	(+)	–	–	–	–	–	–	+ +	–	+ +	+ +	+ + +	–	(+)	–	+ + +	–
P. glauca	+ + +	–	+ +	+ + +	–	–	–	+	(+)	–	+	+	–	(+)	+ + +	+ +	–
P. glauca x sitchensis	–	–	–	–	–	–	+ +	–	–	+ +	–	–	(+)	–	–	–	–
P. mariana	–	–	+	+ + +	–	–	–	–	–	+	–	–	–	–	+	+ +	–
P. sitchensis	–	–	–	–	+ + +	+	+ + +	–	–	–	–	–	–	–	–	–	–
Pinus albicaulis	–	–	–	–	–	–	–	+ +	–	–	–	–	+	–	–	–	–
P. banksiana	–	–	+	+ +	–	–	–	–	–	–	–	–	–	–	–	–	–
P. contorta s. lat.	+ + +	–	(+)	+ + +	+ + +	+ +	+ +	+ + +	(+)	+ +	+ + +	+ + +	+	–	+ +	+ + +	–
P. flexilis	+ +	–	(+)	–	–	–	–	(+)	(+)	–	+	–	–	–	–	–	–
P. monticola	–	–	–	–	–	+	+ +	+	–	+ +	+	+	+	–	–	–	–
P. ponderosa	–	–	–	–	–	–	–	–	–	+	+ + +	–	–	+ + +	–	–	–
Populus balsamifera s. lat.	+ +	–	+ +	+ +	–	+ +	+ +	+	+	+ +	+	+	–	+	+	+ +	(+)
P. tremuloides	+ + +	–	+ + +	+ + +	–	+	+	+	+ +	+ +	+ + +	+ +	–	+ +	+	+ + +	–
Pseudotsuga menziesii	+	–	+	–	–	+ + +	+ + +	+	+	+ +	+ + +	+ + +	(+)	+ +	–	+ +	–
Quercus garryana	–	–	–	–	–	+ +	(+)	–	–	–	–	–	–	–	–	–	–
Thuja plicata	–	–	–	–	+ + +	+ +	+ + +	+	–	+ + +	+ +	+	+	(+)	–	+	–
Tsuga heterophylla	–	–	–	–	+ + +	+	+ + +	+	–	+ + +	+	+	+ +	–	–	(+)	–
T. mertensiana	–	–	–	–	+ +	–	+	+ +	–	+	–	–	+ + +	–	–	–	–

[1] Occurrence classes: + + + (abundant); + + (common); + (present but uncommon); *(+)* (very rare); – (absent).

[2] Zone abbreviations: ALPWS – Aspen-Lodgepole Pine-White Spruce; AT – Alpine Tundra; AWS – Aspen-White Spruce; BWBS – Boreal White and Black Spruce; CCPH – Coastal Cedars-Pine-Hemlock; CDF – Coastal Douglas-fir; CWH – Coastal Western Hemlock; ESSF – Engelmann Spruce-Subalpine Fir; FGP – Fescue Grass Prairie; ICH – Interior Cedar-Hemlock; IDF – Interior Douglas-fir; MS – Montane Spruce; MH – Mountain Hemlock; PPBG – Ponderosa Pine-Bunchgrass; SWB – Spruce-Willow-Birch; SBS – Sub-Boreal Spruce; MGP/SGP – Mixed Grass Prairie/Short Grass Prairie.

[3] Tree species occur only in krummholz form in the Alpine Tundra Zone.

Table 3.—Ecological amplitude of lodgepole pine in selected biogeoclimatic zones of British Columbia.

Biogeoclimatic zone[1]	Occurrence[2] of lodgepole pine in described ecosystem associations
Montane Spruce	24 of 29
Sub-Boreal Spruce	64 of 106
Engelmann Spruce–Subalpine Fir	44 of 80
Boreal White and Black Spruce	12 of 29
Interior Cedar–Hemlock	37 of 92
Interior Douglas-fir	29 of 83

[1] Zones in which lodgepole pine is a major species in British Columbia.

[2] As an abundant or at least frequent species. Sources of information: Mitchell and Green (1981); Coupé, R., and A. R. Yee, editors. (1982. Identification and interpretation of ecosystems of the Cariboo Forest Region. Unpublished report. Ministry of Forests. Williams Lake, British Columbia. 353p.); Utzig, G., D. Macdonald, G. Still, M. Ketcheson, T. Braumandl, and A. Warner. (1983. Ecological classification for the Nelson Region. Unpublished report. Ministry of Forests. Nelson, British Columbia. 79p.); Pojar *et al.* (1984); L. Jang, M. Ketcheson, W. Mitchell, O. Steen, personal communications.

basis for seed zones and seed orchards, a site-specific guide to thinning, fertilization, and prescribed burning, and a broad regional base for forest planning and land use allocation. Some examples of the practical applications and interpretive value of the classification may be found in Klinka (1977), Annas and Coupé (1979), Klinka and Carter (1980), Klinka *et al.* (1980, 1982), Mitchell and Green (1981), Coupé and Yee (1982 *op. cit.*), Corns and Annas (1983 *op. cit.*), Utzig *et al.* (1983 *op. cit.*), and Pojar *et al.* (1984).

As an example, table 6 summarizes silvicultural prescriptions and guidelines for several ecosystem units of the SBSe1 (see Pojar *et al.* 1984). These recommendations are followed in preharvesting silvicultural assessments, management working plans, cutting permit applications, and silvicultural treatments. Additional recommendations might involve stocking standards, thinning regimes, forage seed mixes, habitat suitability for wildlife, etc.

Training

In B.C., development of the classification has been accompanied by an active training program designed for both government and industry personnel. The training emphasis has been on field staff, but courses have also been put on for managers. Courses usually include both office and field sessions. A typical course involves (1) an introduction to the classification system, (2) characterization and description of the biogeoclimatic units that occur in the area where the trainees work, (3) soils (soil-forming processes, diagnostic horizons, dominant soil orders in the area, hand-texturing, humus forms, landforms, moisture/nutrient regimes), (4) identification of ecosystems in both mature forests and clearcuts, and (5) silviculture prescriptions for a series of ecosystem associations in mature forests and clearcuts). Supplementary courses may deal with plant identification and indicator species, soils, and ecosystem mapping. With the aid of field guides that include maps, descriptions, keys, habitat grids, topographic sequences, indicator plant species, and synopses of management interpretations, properly trained personnel are expected to be able to identify and interpret ecosystems in the field.

RESEARCH NEEDS

Priorities for future research in or related to ecosystem classification centre on the two general subjects of ecosystem structure and function. The classification attempts to organize the complexities of ecosystem structure, and there has been much progress in this regard during the past 10-15 years in western Canada. However, basic fieldwork and development of an initial classification still remains to be done in the less developed, less-productive parts of Alberta and B.C. There also remains a need for formalization of the principles and methods of our classification, and a clear explanation of how it works. Consolidation and correlation of the enormous amount of existing information should be a priority. Until recently, seral ecosystems have, for the most part, been ignored or inadequately treated. We need to develop both taxonomic and interpretive classifications of seral ecosystems.

Our understanding of ecosystem function needs to be improved through studies of energy and materials flow within and among ecosystems. More research is required into the processes of humification and mineralization, and the impacts of forest

Table 4. – Prominence values [1] of major plant species in three forested ecosystem associations of the Moist cool northern subzone, western variant (SBSe1) of the Sub-Boreal Spruce Zone.

Strata and species	SBM[2] (17)[3]	MBM1 (39)	MBM2 (20)	DCL (12)
Trees				
Pinus contorta var. *latifolia*[4]	304	171	54	7
Abies lasiocarpa	172	317	470	239
Picea glauca x engelmannii	83	134	191	234
Shrubs				
Vaccinium membranaceum	71	229	25	11
Alnus viridis ssp. *sinuata*	31	15	7	56
Ribes lacustre	T	7	9	47
Rubus parviflorus	T	3	8	169
Oplopanax horridus		T	2	288
Herbs and dwarf shrubs				
Cornus canadensis	69	194	168	66
Linnaea borealis	40	33	21	6
Rubus pedatus	7	71	94	61
Gymnocarpium dryopteris		T	7	230
Mosses and liverworts				
Pleurozium schreberi	575	417	366	55
Ptilium crista-castrensis	96	213	316	62
Hylocomium splendens	15	63	70	33
Barbilophozia lycopodioides	1	12	10	43
Average cover (%) of strata				
Tree	56	53	54	43
Shrub	37	58	40	73
Herb	38	55	48	56
Bryophyte and lichen	70	80	83	47

[1] Prominence value = (mean cover) ($\sqrt{\text{mean frequency}}$). Only species with a prominence value of 40 or more, in at least one association, are included in this table. T (trace) indicates a prominence value of less than 1.

[2] Abbreviations of ecosystem associations: SBM, Submesic bunchberry – moss; MBM1, Mesic bunchberry – moss, black huckleberry subassociation; MBM2, Mesic bunchberry – moss, five-leaved bramble subassociation; DCL, Devil's club.

[3] Number of stands sampled appears in parentheses.

[4] Nomenclature follows Pojar *et al.* (1982).

Table 5. – Habitat features of selected ecosystem units of the Moist cool northern subzone, western variant (SBSe1) of the Sub-Boreal Spruce Zone.

	SBM[1]		MBM1		MBM2		DCL	
	a	b	a	b	a	b	a	b
Habitat features	(17)[2]		(39)		(20)		(12)	
Slope (%)	0 - 50		0 - 40		0 - 27		2 - 55	
range and (mean)	(14)		(12)		(18)		(18)	
Slope position	Upper, flat		Middle		Middle, lower		Lower, toe	
Soil parent materials[3]	F, FG, M	M	M, FG	M	F, FG	M	F	M
Particle size classes[4]	CL, S	FL	CL, LS	FL	CL, SS	FL, C	LS, SS	FL, C
Drainage class[5]	W	MW	W, MW	MW, I	R, MW	MW, I	R, MW	MW, I
Moisture regime	Submesic		Mesic		Mesic – subhygric		Subhygric – hygric	
Nutrient regime	Medium		Medium		Medium – rich		Rich	
Soil classification[6]	DYB, HFP	GL	HFP, DYB	GL, DYB	DYB, R	GL	DYB, EB	GL, G, EB
Humus form classification[7]	HMR		HMR	HMR, MMR	HMR		HMR, HUMR, MMR	
Rooting depth (cm)	50		49	30	63	35	54	
Thickness mineral soil (cm)	55		49	60	31	78	56	
Thickness humus layer (cm)	5		9		8		15	
Mineral soil pH[8]	4.7		4.3		4.3		5.7	
Humus pH[8]	3.6		3.7		4.0		4.8	

[1] Abbreviations of ecosystem units: SBM, Submesic bunchberry – moss association, a – coarse textured phase, b – fine textured phase; MBM1, Mesic bunchberry – moss, black huckleberry subassociation, a – coarse textured phase, b – fine textured phase; MBM2, Mesic bunchberry – moss, five-leaved bramble subassociation, a – coarse textured phase, b – fine textured phase; DCL, Devil's club association, a – coarse textured phase, b – fine textured phase.

[2] Number of stands sampled appear in parentheses.

[3] Abbreviations of soil parent materials: F, fluvial, FG, glaciofluvial, M, morainal.

[4] Particle size classes follow Canada Soil Survey Committee (1978). Abbreviations: C, clayey; CL, coarse loamy; FL, fine loamy; LS, loamy skeletal; S, sandy; SS, sandy skeletal.

[5] Drainage classes: I, imperfectly; MW, moderately well; R, rapidly; W, well.

[6] Soil classification follows Canada Soil Survey Committee (1978). Abbreviations: DYB, Dystric Brunisols; EB, Eutric Brunisols; G, Gleysols; GL, Gray Luvisols; HFP, Humo-Ferric Podzols; R, Regosols.

[7] Humus form classification after Klinka *et al.* (1981). Abbreviations: HMR, Hemimors; HUMR, Humimors; MMR, Mormoders.

[8] In $CaCl_2$.

management on these processes. More studies into ecological methods of assessing site productivity would be desirable, as would ecosystematic growth and yield studies. Successional processes and pathways need to be elucidated, and successional models developed, with consideration of the implications for wildlife and range management as well as for forestry. We also require more information on the effects of fire on ecosystems and the use of fire in resource management; similar information is required for herbicides.

Finally, there is an urgent need for researchers to help develop and use a system of ecological reserves or research natural areas.

Table 6.—Summary of silvicultural prescriptions and guidelines for selected ecosystem units of the Moist cool northern subzone, western variant (SBSe1) of the Sub-Boreal Spruce Zone.

Silvicultural prescriptions and guidlines	SBM[1]	MBM1		MBM2		DCL	
		a	b	a	b	a	b
Season of logging	Sum[2], (win)	Sum[2] (win)	Win (sum)[3]	Sum, win	Win, sum[3]	Win, sum[3]	Win
Prescribed fire	Avoid	Avoid	OK[4]	OK[4]	OK	OK	OK
Species selection preferred	lodgepole pine	pine	pine	pine spruce	spruce pine	spruce pine	spruce
acceptable		spruce[5]	spruce[5]		fir[5]	fir	pine[6]
unacceptable	hybrid spruce subalpine fir	fir	fir	fir	(fir)		(pine)
Regen. method	Nat. or plant	Na/pl	Na/pl	Na/pl	Pl/na	Pl	Pl
Max. regen. delay (yrs.)	8	8	8	8	8	2-3	2-3
Free growing[7] survey (yrs. from establ.)	4-6	4-6	4-6	4-6	4-6	8-11	8-11
Minimum height growth[8] (cm)	(18)	(18)	12(18)	12(18)	12(18)	18(30)	18(30)
Brush[9] potential	V Low	Low[10]	Low-moderate	Low	Low-moderate	High	V High
Brushing and weeding			As reqd		As reqd	Usually reqd	reqd

[1] Abbreviations of ecosystem units: SBM, Submesic bunchberry—moss association: MBM1, Mesic bunchberry—moss, black huckleberry subassociation, a—coarse textured phase, b—fine textured phase; MBM2, Mesic bunchberry—moss, five-leaved bramble subassociation, a—coarse textured phase, b—fine textured phase; DCL, Devil's club association, a—coarse textured phase, b—fine textured phase.

[2] Summer logging if aiming for natural regeneration.

[3] During dry spells.

[4] If only the litter humus layer (L) removed, and if followed by planting.

[5] As a minor (less than 20% of total crop trees present) component of the stand; natural regeneration only.

[6] As a minor component of stand, and only on better drained microsites.

[7] Free-growing tree when last whorl is equal or above competing vegetation.

[8] For all commercial tree species; figures for lodgepole pine only in parentheses.

[9] All deciduous trees, shrubs, and herbs that inhibit the establishment and growth of selected coniferous tree species.

[10] Sitka alder (*Alnus viridis ssp. sinuata*) can cause problems.

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SOILS AND PRODUCTIVITY OF LODGEPOLE PINE

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ABSTRACT

Lodgepole pine seeds do not germinate well on soils that are dry and cold at the surface in the spring. Frost heaving can kill new germinants and partially destroy roots of older seedlings, slowing their growth. Productivity of lodgepole pine is restricted in some soils by barriers to root proliferation, such as restrictive layers or high water tables. When such barriers are absent, productivity increases with increased availability of water. Increased nutrient availability should also increase productivity, but characteristics that should reflect increased nutrient availability are not always significantly correlated with increased productivity in field studies. Organisms that cause root and butt rots are probably related to certain soil characteristics, such as pH and degree of surface compaction, but work in this area has been limited in lodgepole pine stands.

INTRODUCTION

Within the wide geographic and elevational ranges of lodgepole pine (*Pinus contorta* Dougl.), many different soils occur. Stands of the three major varieties (var. *latifolia* Engelm.), Sierra lodgepole (var. *murrayana* (Grev. and Balf.) Engelm.), and shore pine (var. *contorta* Dougl.) grow best, if not too dense in medium-textured soils with high amounts of available water and nutrients in the absence of competition from associated species. These varieties, however, also grow in wet, poorly drained soils, in very infertile soils, in shallow dry soils (Lotan and Perry 1983), and in cold soils in flats and basins subject to a high incidence of radiation frost (Cochran 1973) where the species has a competitive advantage over its common associates. These varieties exist in sand, gravel, and volcanic pumice with very low organic matter contents but they also invade wet meadows with high soil organic matter contents. Lodgepole pine occurs naturally in peat in Alaska (Ugolini and Mann 1979), British Columbia, and western Washington (Lotan and Perry 1983), and all three varieties have been established in peat in northwestern Europe (Lines 1968).

Soils supporting lodgepole pine usually have a mean annual soil temperature at 20 inches (50 cm) of less than 47° F (8° C). In Montana, soils derived from dolomite limestone, which have free lime in the upper 20 inches (50 cm) and a pH near 8, exclude lodgepole pine. Lodgepole pine is found, however, in soils developing from other types of limestone and calcareous glacial till where free lime is leached below 20 inches (50 cm) and the pH of the surface horizon is 7.0 or less (Lotan and Perry 1983). Dumanski and others (1973) reported that a pH of 5.5 to 6 is optimal for productivity in the Hinton-Edson areas of Alberta.

Even-aged stands at times transect a range of soil conditions as changes in topography, drainage, and soil parent material occur. For stands encompassing different soil conditions, productivity can vary with certain soil characteristics related to availability of water and nutrients. Yet changes in productivity within other stands, reflected in growth rates of individual trees or in stocking levels, are not always related to easily detected differences in soil characteristics.

Productivity is related to soils in one or more of the following ways:

1. The ability of seeds to germinate and produce seedlings that will become established.
2. The ability of roots to proliferate through the soil.
3. The ability of soil to supply water and nutrients.
4. The degree of soil aeration.

In addition, there may also be some relationship between soil characteristics and mycorrhizae that aid nutrition and other organisms causing root and butt rots.

GERMINATION AND ESTABLISHMENT

Lodgepole pine is usually pictured as a seral species, a prolific seeder quickly invading and establishing dominance after fire or other disturbance (Eis and others 1982). There are sites, however, where lodgepole pine is considered an edaphic or topoedaphic climax (Youngberg and Dyrness 1959, Stephens 1966, Moir 1969, Despain 1983, Volland, this symposium). Further, stand establishment can be difficult because of soil and climatic conditions.

A sequence of events is necessary for establishment of stands from seed. Adequate seed must be produced and distributed over the area, and germination must occur. For high elevation sites with a relatively dry air mass, a high incidence of clear skies, and soils with low heat capacities and thermal conductivities, there must be the right combination of soil water content and soil temperature for germination to occur every spring. The surface layer of the soil may dry out before the temperature warms enough for seeds to germinate. When germination does occur, soil and weather conditions must minimize frost heaving, radiation frost, and high afternoon temperatures at the soil-air interface. High temperatures at the surface or drought can also cause mortality throughout the summer. If soils become wet in the fall without becoming snow covered, frost heaving can kill the seedlings that have survived through the summer

(Cochran 1973). Severe frost heaving can also occur in the winter, under the right conditions, and in the spring the year after germination.

Frost heaving starts in an unfrozen soil that is wet up to the surface. When the temperature dips below freezing late in the day, water in a thin surface layer quickly freezes. Water then begins to migrate upward from the unfrozen soil below the surface to the frozen layer where it also freezes. As the pores in the frozen layer become occupied with ice, the ice crystals begin to elongate as more water continues to arrive from below. As these ice crystals form and elongate on successive nights, the frozen surface layer is displaced upward and separated from the unfrozen soil below. Plants with root collars incased in the frozen layer are pulled upward (Cochran 1975).

A combination of poor germination, extreme temperature at the soil surface, and frost heaving results in low stocking on some sites. Frost heaving may also lengthen the establishment period for seedlings not killed outright. Partial heaving may destroy a portion of the root system, perhaps annually on susceptible sites, resulting in very slow juvenile growth.

ROOT PROLIFERATION

Root development of lodgepole pine is highly variable (Horton 1958) and partly dependent on soil characteristics. During seedling and sapling development in well-drained, medium-textured soils, the tap root is dominant but gradually becomes less significant as trees mature. Sinker roots develop near the base of lateral roots and provide the major support after the trees reach pole size. Vertical rooting is limited by coarse or restrictive layers or high water tables. Roots bend, die, or become convoluted or clubbed (Smithers 1961).

In pumice soils or soils with coarse or restrictive layers, root development is often confined to a shallow system of laterals. Unless some sinker roots can penetrate through the pumice or other restrictive horizons and develop a second layer of lateral roots, the trees are susceptible to windthrow. Where restrictive soil horizons occur, growth rates are much reduced because the roots have less access to water and nutrients. Such growth reduction is occasionally evident in mixed stands of ponderosa and lodgepole pine growing in soils that have unweathered pumice horizons 4 feet (1.2 m) or more thick. The ponderosa pine root system is able, with time, to penetrate through the pumice and utilize the water and nutrients in the older, buried profile. A substantial increase in growth is evident as soon as the roots enter the buried soil (Herman and Peterson 1969). Lodgepole pine has difficulty forcing its roots through pumice particles that are bridged together (Cochran 1971) and is unable to reach older, buried soil. In this situation, ponderosa pine trees appear vigorous whereas lodgepole pine trees appear to be under severe stress.

Restrictions to root proliferation of lodgepole pine can also occur in soils without highly noticeable restrictive layers. When Base and Fosberg (1971) studied the relationship between site quality and certain soil characteristics in northern Idaho, they found that site index of lodgepole pine was significantly related to the moist consistency of the most developed horizon in the upper 40 inches (1.0 m). They believe this moist consistency is a reflection of root penetrability. Pluth (1983) also found that consistency of the B horizon was related to lodgepole pine productivity in Alberta.

WATER AND NUTRIENT AVAILABILITY

Lodgepole pine often grows under nutrient conditions considered less than optimal for most conifers. Although fertilization studies have shown significant increases in growth rates (Weetman and others, this symposium), other studies have found little correlation between soil nutrient levels and growth. Lodgepole pine may occupy a low nutrient niche, either through a low nutrient requirement or an ability to extract nutrients unavailable to other species (Lotan and Perry 1983). Difficulty in determining the availability of soil nutrients may partially account for the lack of correlation between soil nutrient levels and growth. Some studies have shown correlations between productivity and soil factors related to both water and nutrient availability, whereas other studies have found productivity to be correlated with water availability alone.

Mason and Tigner (1972) investigated some relationships between productivity and soil characteristics while studying a needle miner (*Coleotechnites* near *milleri*) outbreak in central Oregon. They examined stands transecting drainages, dry basins, and slopes. Highest stand densities and greatest radial increments ocurred in drainages where A horizons were thickest and the available water was highest. Radial increment and available water were lowest on slopes and intermediate for basins. Mason and Tigner also found slightly lower concentrations of nitrogen in first-year foliage from slope plots (0.92 and 0.90 percent for two locations) than for basins (1.04 and 1.03 percent) and drainages (1.02 and 1.12 percent).

Youngberg and Dahms (1970) also investigated productivity of lodgepole pine in central Oregon. They found productivity could not be delineated by soil series alone. Significant differences within one soil series (Lapine) were recognizable, however, on the basis of total thickness of the pumice mantle and the combined thickness of the A and AC horizons. A better indication of productivity was based on understory communities.

Mogren and Dolph (1972) examined a spectrum of environmental variables in relation to site index for lodgepole pine in northern Colorado and southern Wyoming. Using multiple regression techniques, they found site index to be related to the percent by weight of particles larger than 0.25 millimeters in diameter in the A horizon, total depth of soil to the top of the C horizon, estimated surface stoniness, and average annual precipitation. Several additional factors were analyzed and found not to be significant. Mogren and Dolph concluded that all factors significantly correlated with site index were apparently related to soil water availability.

Illingworth and Arlidge (1960) report that volume production of lodgepole pine in British Columbia decreases with decreasing available water. Duffy (1964) found that total volume per acre is negatively and weakly correlated with pH and shallowness of the lime layer for the Lobly soil series in Alberta, but that other correlations between nutrient levels and pine growth were too weak for predictive purposes. Duffy did find some factors related to available soil water (slope position for the Lobly series and slope grade for the Horburg series) to be potentially useful in predicting lodgepole pine productivity.

AERATION

Aeration, the exchange of oxygen and carbon dioxide between the atmosphere and the soil and plant roots, is reduced by high soil water contents. This reduction in aeration reduces the aerobic respiration of both higher plants and the soil microorganisms. These reductions in respiration rates influence the rates at which nutrients become available and the rates at which they are used by higher plants.

Although lodgepole pine seeds can germinate and the seedlings can survive in very wet soils with low oxygen diffusion rates (Cochran 1972, Minore 1970), productivity is restricted (Dumanski and others 1973). Pluth (1983) found productivity was significantly related to depth of mottles. Boggie and Miller (1976) found that stem volume, tree weight, and photosynthetic leaf area increased exponentially and height growth of lodgepole pine increased linearly with increasing dryness of peat in Scotland.

ROOT DISEASES AND SOILS

Flammula alnicola causes a yellow, stringy root rot occasionally on lodgepole pine in Canada. More important root rots in lodgepole pine are caused by *Armillaria mellea, Fomes annosus, Ployporus tomentosus,* and *P. schweinitzii.* Lodgepole pine is also moderately susceptible to attack by *Poria weirii* in the Pacific Northwest. *Coniophora puteana* also causes butt rot in Colorado (Hepting 1971).

The relationship between soil conditions and these root diseases is not clear. Sites with low pH (Singh 1983); low N, P, and Ca, and high K (Shields and Hobbs 1979); and surface soil compaction (Ono 1970) were found to be most susceptible to *Armillaria.* Whitney (1966) reports that *Polyporus tomentosus* grows best at a pH of 4.5 but will grow well over a range of 3.5 to 6, suggesting a reason for the absence of this disease on alkaline soils. More specific information relating the incidence and severity of these diseases in lodgepole pine with various soil factors is not available.

CONCLUSIONS

Lodgepole pine is adaptable to a wide variety of soils, at times growing where its common associates cannot compete. The only soil factor that appears to limit its existence within its range is a pH approaching 8. Since lodgepole pine is an edaphic or a topo-edaphic climax on some sites because other species either do not survive or do not grow well, managers should be careful about converting certain lodgepole stands to other species. Although lodgepole pine is usually easy to regenerate, regeneration on some sites can be difficult, particularly where lodgepole pine is climax. Poor management of these sites might produce barren areas. Because of its rooting characteristics, lodgepole pine may be particularly susceptible to growth loss resulting from soil compaction. Managers should be careful about operating equipment in lodgepole pine stands when soils are wet and subject to compaction.

As lodgepole pine comes under intensive management, forest managers will need more specific information on soils and lodgepole pine productivity. Additional studies on gross growth, levels of growing stock, and fertilization are needed to define potential growth rates and growth rates over a range of stand densities with and without fertilizer application. Study sites should be located over the geographic range of lodgepole pine and in all habitats where lodgepole pine will be managed for timber production.

In conjunction with growth studies, there should be additional investigations to determine the biological reasons for differences in growth rates. These investigations would include studies of nutrient uptake in relation to various measures of nutrient availability and application rates as well as the relationship of plant water stress and the soil water regime.

More knowledge of the biology of the species interpreted in relation to rates of growth will allow design of better simulation models and more effective planning for future management of the lodgepole pine resource.

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FACTORS INFLUENCING PRODUCTIVITIES

SMALL MAMMAL DAMAGE AGENTS WHICH AFFECT THE INTENSIVE SILVICULTURE OF LODGEPOLE PINE

Thomas P. Sullivan

ABSTRACT

Feeding damage by the snowshoe hare, red squirrel, and porcupine may adversely affect seedling and sapling stages of lodgepole pine silviculture. Hares browse seedlings and, along with squirrels and porcupines, bark and girdle pole-size trees. Pocket gophers and voles also inflict feeding damage on seedlings.

Snowshoe hare populations reach a peak in abundance every 9-10 years and cause serious damage to plantations in central and northern Alberta as well as some northeastern parts of British Columbia. Population reduction, mechanical habitat alteration, and standard chemical repellents have failed to control hares and their feeding damage. A biological repellent system based on predator odours and encapsulation in timed-release devices is currently being developed. Compounds from weasel family scent gland odours have been particularly effective in suppressing hare feeding on lodgepole pine seedlings. This area repellent system may also eventually be used for protection of pole-sized stands as well.

Long-term studies of the impact of hare and squirrel damage on growth and yield in thinned stands of juvenile pine was begun in 1979 in the Prince George and Cariboo Forest Regions of B.C. Semi-girdling (sub-lethal) damage clearly suppressed diameter growth of crop trees in the first three years after thinning. Frequency of attack and proportion of girdled and semi-girdled trees were significantly related to diameter: hares prefer stems less than 60 mm d.b.h. whereas squirrels (and porcupines) prefer stems greater than 60 mm d.b.h. Thinning of juvenile stands should be coordinated with low hare populations to prevent damage and allow crop trees to grow beyond 60 mm d.b.h. before the next peak population. A silvicultural strategy for alleviating squirrel damage is currently being investigated.

INTRODUCTION

Intensive forest management requires many silvicultural techniques such as planting, thinning, fertilization, and weeding to produce a stand of commercial value in an acceptable rotation period. Lodgepole pine (*Pinus contorta* var. *latifolia*) shows favourable growth and yield responses to silvicultural treatments such as stocking control and fertilization. Thus, it is a very suitable tree species for the rapid biomass production necessary to maintain supplies of lumber, pulp, and paper. However, the seedling (plantation) and sapling or pole-size (juvenile stand) stages of managed lodgepole pine forests are particularly vulnerable to feeding attacks by small mammals.

The distribution of lodgepole pine in western North America coincides with the ranges of several small mammal damage agents. The species responsible for most of the damage to lodgepole pine are the snowshoe hare (*Lepus americanus*), red squirrel (*Tamiasciurus hudsonicus*), porcupine (*Erethizon dorsatum*), pocket gophers (*Thomomys* spp.) and several voles (*Microtus* spp.).

This paper will discuss the interaction of mammal damage with the various aspects of lodgepole pine silviculture from newly-planted seedlings to pole-size stems. The discussion will concentrate on the silvicultural techniques of plantation establishment, spacing/thinning, and fertilization. Management strategies for alleviating damage from each mammal species will be derived from completed studies and those currently in progress.

PLANTATION SEEDLINGS

Snowshoe Hares

Damage to lodgepole pine plantations by snowshoe hares has been reported in many areas of northwestern Canada (specifically western Alberta and central British Columbia). This animal damages coniferous seedlings by clipping the leader and/or lateral shoots (Lawrence *et al.* 1961). In general, the extent and important economic significance of this browsing damage to reforestation has been clearly shown in Washington and Oregon (Black *et al.* 1979; Brodie *et al.* 1979). However, although the importance of the problem is increasing rapidly in northern B.C. and Alberta as reforestation intensifies, little quantitative work in damage surveys has been done. Preliminary assessments in northern Alberta indicated that newly-planted areas of seedlings could be entirely devastated by snowshoe hare feeding (Keith 1972).

A characteristic feature of the snowshoe hare is the 9-10 year cyclic fluctuation in abundance (Keith 1963; Keith and Windberg 1978). This cycling behavior occurs throughout much of Canada but exhibits its most dramatic changes in numbers of hares in central and northern regions of its range. During peak years of abundance, hares severely browse seedlings in plantations during winter months when their alternative preferred foods (various deciduous plant species) are scarce.

The historical record of cyclic fluctuations in snowshoe hares goes back at least 200 years. The hare cycle will continue throughout the boreal and sub-boreal forests of Canada for many more. Thus, several management techniques have been suggested to achieve restocking of lodgepole pine in northern B.C. and Alberta:

1. plant mainly during the predictable 5- to 6-year period (between peaks) of relatively low hare populations
2. use larger stock for planting
3. use wildlings (no nursery fertilization regime which boosts palatability) which may be inherently less susceptible to attack
4. continue shrub control after initial site preparation – habitat manipulation with herbicides
5. use a repellent system during the one to three years when peak populations exist

These recommendations have not been rigorously tested on an experimental basis but are designed to obtain sufficient seedling growth to get lodgepole pine seedlings beyond the stage of critical hare damage. Such trees should probably be at least 2 m in height. Population reduction by poison/ shooting/trapping has also received much attention but is not an effective method because of the rapid colonization of depopulated areas by hares. Of the above recommendations, only (4) and (5) are considered flexible enough alternatives for reforestation programs. Habitat manipulation coupled with a durable repellent system could provide effective protection for northern plantations.

Habitat Manipulation

Snowshoe hares clearly prefer habitats which provide good cover such as overstocked stands of conifers and logged or burned areas with abundant growth of herbs and shrubs (Borrecco 1976; Wolfe *et al.* 1982; Pietz and Tester 1983; Parker 1984). Habitat manipulation with a herbicide-induced reduction in vegetative cover and availability of summer foods resulted in a significant reduction of damage to Douglas-fir (*Pseudotsuga menziesii*) seedlings by snowshoe hares (Borrecco 1976). A similar experiment using mechanical scarification reduced the abundance of hares but did not alleviate damage to planted seedlings (Sullivan, T. P. and Moses, R. A. in preparation). Thus, habitat alteration with herbicides may provide a more complete reduction in vegetative cover (and food) and hare damage than that obtained by mechanical means.

Repellent System

The majority of animal repellents which are commercially available were developed because of their distasteful odour to man rather than to the problem animal. This makes the unlikely assumption that herbivores have the same olfactory limits and preferences as man. A repellent must elicit fear, not simply "displeasure," such as would be the result of a repugnant chemical. An effective repellent should result in an immediate and long-lasting avoidance of the source of that odour. Thus, a project was initiated to develop biological repellents based on mammalian predator odours which could be encapsulated in a timed-release system to provide long-term protection for plantations of lodgepole pine (and other conifers).

The effectiveness of predator odours (fecal, urine, and anal scent gland) in suppressing feeding damage by snowshoe hares was investigated in pen bioassays at the University of British Columbia Research Forest, Maple Ridge, B.C., Canada. A total of 28 bioassay trials tested the effects of these odours on hare consumption of willow browse and coniferous seedlings. Lynx-bobcat feces, weasel scent gland secretion, and several predator urines resulted in the most effective suppression of hare feeding damage. A field bioassay with lodgepole pine seedlings and weasel scent provided significant results comparable to the pen bioassays.

Identification and synthesis of the active compounds in the weasel scent gland secretion yielded several potential repellents. These candidate compounds were field tested on 3-year-old lodgepole pine seedlings at a site near Prince George, B.C. Results of this field bioassay are listed in table 1. 3-Propyl-1,2-dithiolane completely suppressed hare feeding on lodgepole pine seedlings during the 5-week experiment (trial A). Control seedlings were essentially all consumed by hares at day 12. 2,2-Dimethylthietane was also reasonably effective in suppressing hare feeding but was not statistically (chi-square) different from 3-propyl-1,2-dithiolane. The third compound, 2-propylthietane, did not improve seedling survival over that of control seedlings. These field results corroborate those obtained in earlier pen bioassays (Sullivan and Crump 1984).

These weasel scent gland components may be used as fear or avoidance inducing compounds encapsulated in timed-release devices. Their use as area repellents to protect lodgepole pine plantations from hare damage is clearly of considerable value to the intensive management of this tree species. Additional active components from other predator odour formulations are currently being investigated.

Pocket Gophers

Pocket gopher (*Thomomys* spp.) damage to young (up to 10 years) plantations has received much attention in lodgepole pine and ponderosa pine (*P. ponderosa*) areas of the Pacific Northwest. Damage is most severe east of the Cascade Range in Washington and Oregon as well as in some areas of Idaho. These burrowing rodents damage seedlings by root pruning and a combination of stem girdling and clipping (Ronco 1967; Crouch 1969, 1971; Barnes 1973). Seedlings are frequently clipped at or near ground level and the roots or stems are taken. Damage occurs year-round but is most frequent in winter.

Lodgepole pine is now the dominant commercial timber species in the southern interior of B.C. Regeneration

Table 1.—Field efficacy (% seedlings surviving) of mustelid compounds: 3-propyl-1,2-dithiolane, 2,2-dimethylthietane, and 2-propylthietane in suppressing snowshoe hare browsing on lodgepole pine seedlings. Trials were terminated on May 14 (day 38/26) as hares had switched to summer herbaceous foods and were no longer feeding on coniferous material.

	Days					
	0 (April 6)	5	12	17	23	38 (May 14)
Trial A						
Control	100.0	82.0	10.0	6.0	6.0	0.0
3-PDIT	100.0	100.0	100.0	100.0	100.0	100.0
2,2-DMT	100.0	100.0	90.0	78.0	78.0	78.0
			Days			
			0 (April 18)	5	11	26 (May 14)
Trial B						
Control			100.0	48.0	38.0	38.0
2-PT			100.0	52.0	42.0	42.0

naturally or by planting forms the basis of intensive silviculture in this area. Since the pocket gopher ranges throughout the lodgepole pine areas of the southern interior, it is only a matter of time before plantation seedlings are attacked by this animal.

Burrowing animals are very difficult to eliminate by conventional means. Pocket gophers are no exception with some success achieved by placing poison in their burrows. However, such positive results are usually overshadowed by the hazard of poison to non-target animals which frequent the same habitat. To be effective, poisoning must follow strict guidelines, and more than one application per year over several years may be needed (Crouch 1982). Thus, it is not surprising that gopher damage is one of the most perplexing problems confronting foresters in the western United States.

Several studies have reported a reduction in gopher abundance after removal of their food supply with herbicides (Crouch and Hafenstein 1977; Black and Hooven 1977; Crouch 1979). Control of gophers with herbicides shows promise for lodgepole pine plantations, particularly if shrub control was a desirable concurrent objective.

Silvicultural manipulation by planting more than the standard number of trees might improve the success of gopher-threatened plantations of lodgepole pine. This might increase the number of trees which escape damage (Crouch 1982). Similarly, regeneration logging systems should be designed to protect seed-producing trees and advanced regeneration, to open stands only enough to allow regeneration, and to minimize disturbance of understory (Crouch 1982). In general, site disturbance without complete, long-term removal of herbage usually improves gopher habitat.

Voles

Lodgepole pine seedlings in plantations associated with grassy habitat are susceptible to damage by voles. Instances of severe attack are erratic in geographic distribution and frequency of occurrence in western North America. However, voles are a serious problem in lodgepole pine plantations in Scandinavia (Roll-Hansen and Roll-Hansen 1977; Edstedt 1979; Hansson and Bostrom 1979). These animals usually girdle seedlings by gnawing stems above ground level (Lawrence *et al.* 1961). Most species of *Microtus* have 2-5 year cyclic fluctuations in density.

The most common voles in interior lodgepole pine forests of western North America are the meadow mouse (*M. pennsylvanicus*) and long-tailed vole (*M. longicaudus*) which may occasionally attack planted seedlings during peak population outbreaks. Voles will also clip germinants of lodgepole pine (Wagg 1963). In general, control of grasses and associated vegetative cover in plantations is the most effective method of preventing vole population buildups and damage.

SPACING/THINNING OF JUVENILE STANDS

Snowshoe Hares

Stands of juvenile lodgepole pine covering burned-over forest land have become increasingly valuable to forestry in western North America. This species responds favourably to stocking control (spacing or thinning) and fertilization. However, overstocked pine stands provide optimum habitat for populations of snowshoe hares (Adams 1959; Grange 1965; Koehler *et al.* 1979).

Hare barking and girdling injuries to coniferous stems have been recorded by several authors (Bider 1961; Lawrence *et al.* 1961; Dé Vos 1964; Lloyd-Smith and Piene 1981). A detailed description of hair barking injuries to lodgepole pine in central B.C. has been discussed by Sullivan and Sullivan (1982a), and in Alberta reported by Johnstone (1981) and Powell (1982). These feeding injuries during the overwinter period are characterized by gnawing and removal of bark which is then eaten by the animal. Until recently, bark removal by hares (and squirrels) was considered to be of little importance to forest management. However, with the advent of intensive silviculture of young coniferous stands in Canada and the United States, barking and girdling injuries will receive much greater attention.

Damage Assessment and Impact on Growth

A study initiated in 1979 measured the impact of snowshoe hare feeding on lodgepole pine during the first four years after spacing (Sullivan 1984). An 18-year-old stand, 20 km east of Prince George, B.C., (fig. 1) was manually spaced (2 m x 2 m) in 1979. Hare feeding damage and populations were monitored from 1979 to 1983 in the spaced and a nearby control (unspaced) stand. The study period corresponded with the late increase, peak, and decline phases of the 10-year hare population cycle. Negligible damage to crop trees was recorded in the first winter after spacing as hares fed on the foliage from felled trees (fig. 2). Feeding attacks to spaced trees increased dramatically (74.8% trees damaged) in the subsequent winter before declining to 18.5% and 14.3% during the third and fourth winters, respectively. Damage to unspaced crop trees varied from 24.5 to 69.1% during this period.

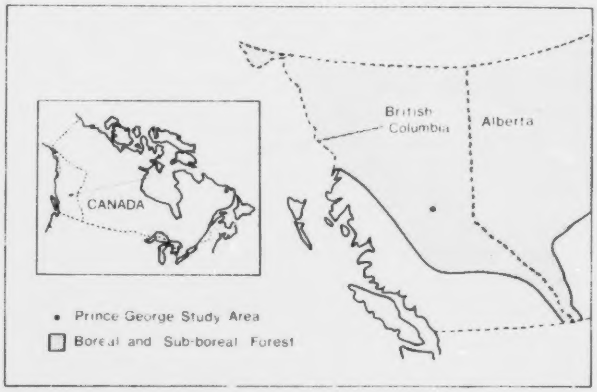


Figure 1. – Location of study area near Prince George, B.C. where a long-term study of snowshoe hare and red squirrel damage to lodgepole pine has been ongoing since 1979.

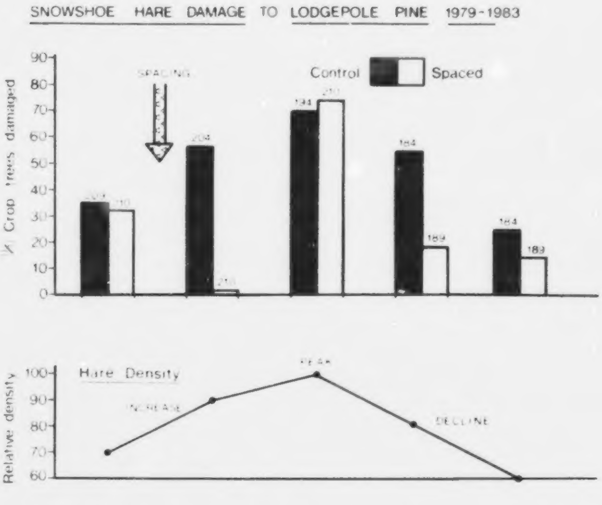


Figure 2. – Relationship between damage intensity and phase of population cycle for control and spaced stands during the period 1979 to 1983. Total number of sample crop trees is located above bars.

The total percentage of girdled and semi-girdled (≥ 50% of circumference) stems was 18.1% in the spaced and 30.1% in the control stand. Semi-girdling (sub-lethal) damage clearly suppressed diameter growth of crop trees in both stands (fig. 3B). In general, diameter increment of spaced trees was greater than controls (fig. 3C).

The total amount of bark and vascular tissue removed did not appear to affect diameter growth during the first three years after spacing. The spatial distribution of girdling and semi-girdling injuries tended to be clumped over the area of the control stand. In general, the frequency of attack and proportion of girdled and semi-girdled trees were significantly greater among small (< 60 mm dbh) than large trees (fig. 3A). Stands with fewer than 15,000 stems/ha have relatively large average diameters, and hence may be spaced with little compensation for future crop tree loss to hares. Sullivan and Sullivan (1983) provided an index of pine density levels which may be susceptible to hare damage when such stands are operationally spaced.

Recommendations to Alleviate Damage

Several silvicultural recommendations to alleviate hare damage to spaced lodgepole pine are as follows (Sullivan 1984):

1. Juvenile spacing of overstocked stands of lodgepole pine which are susceptible (> 15,000 stems/ha) to hare damage should be delayed until the potential crop trees are > 60 mm in average dbh. Overstocked stands < 15,000 stems/ha may be spaced without concern for potential hare damage.
2. Stands with potential crop trees of average dbh < 60 mm may be spaced during the peak year or first year of the decline in the hare population cycle. One year with minimal

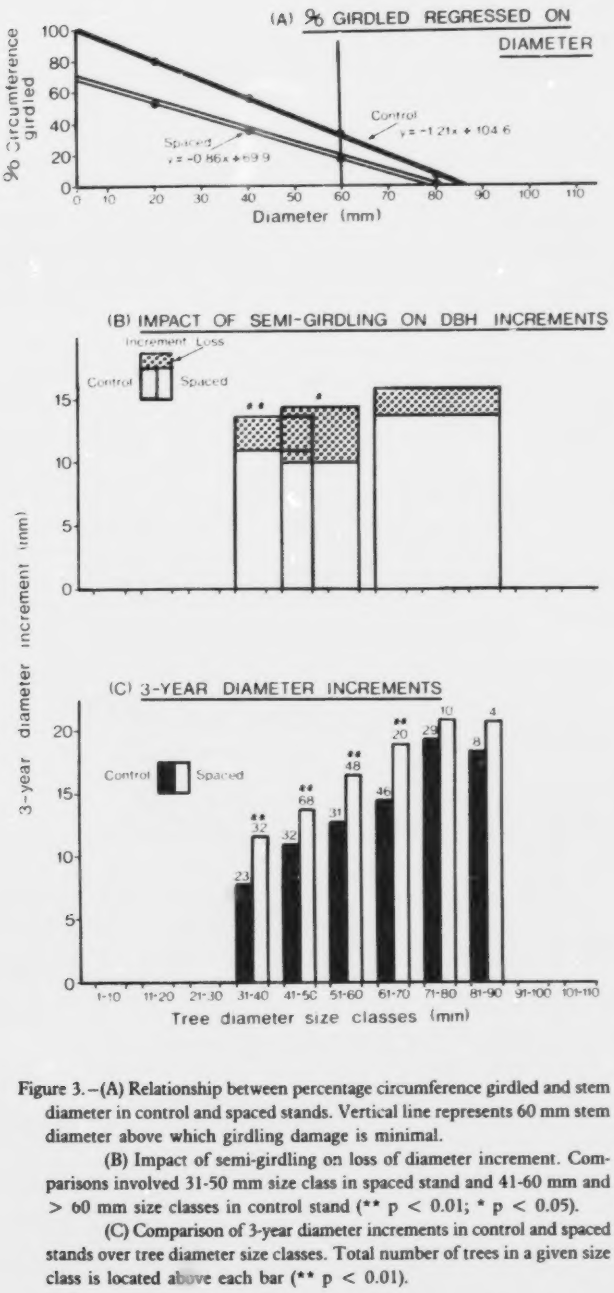


Figure 3.—(A) Relationship between percentage circumference girdled and stem diameter in control and spaced stands. Vertical line represents 60 mm stem diameter above which girdling damage is minimal.

(B) Impact of semi-girdling on loss of diameter increment. Comparisons involved 31-50 mm size class in spaced stand and 41-60 mm and > 60 mm size classes in control stand (** $p < 0.01$; * $p < 0.05$).

(C) Comparison of 3-year diameter increments in control and spaced stands over tree diameter size classes. Total number of trees in a given size class is located above each bar (** $p < 0.01$).

damage will follow because of the fallen pine foliage acting as an alternative food source. However, crop trees must be of sufficient initial size to reach > 60 mm dbh during the 6 to 7 years before the next hare population increase (1988).

3. In stands with a wide range of size classes, choose large (> 60 mm dbh) crop trees and, if necessary, leave smaller stems as sacrifice food for hares.
4. A 2-step spacing program is the most flexible approach. This strategy would space stands in two stages dependent on stand age and site factors. Small mammal damage to closely spaced stands after the initial treatment could be assessed and the level of treatment in the second stage could compensate for tree mortality without serious crop tree loss. This second stage thinning assumes that stems have grown beyond susceptibility to hare damage before the stand is treated and that other potential mortality factors such as disease or insect attack do not appreciably lower the final crop tree density.
5. In terms of area, spacing operations should cover as large an area as possible to render the habitat (spaced stand) less attractive to hare populations over time.
6. Develop a timed-release biological repellent system (discussed earlier) or a systemic repellent to reduce hare damage during all phases of the population cycle.

These recommendations cannot be applied to coniferous plantations which, in most cases, must outgrow and survive two and probably three peaks of snowshoe hare populations in central and northern regions of B.C. After this time, trees will presumably have reached a stage where they could be spaced on the basis of crop tree selection.

Red Squirrels

The red squirrel is another serious damage agent which attacks young lodgepole pine. This animal peels away the outer bark to feed on phloem and cambial tissues during the spring and early summer (Lawrence *et al.* 1961; Sullivan and Sullivan 1982a). Rapidly growing crop trees within thinned stands of lodgepole pine are particularly susceptible to squirrel feeding injuries. Annual damage measurements since 1979 at Prince George and a regional assessment of small mammal damage in the Cariboo in 1981 confirmed the importance of squirrel damage to lodgepole pine in these regions. In general, squirrel damage may be locally present in all lodgepole pine regions of western North America.

Damage Assessment and Impact on Growth

The poorly-defined pattern of population fluctuation in red squirrels suggested that they could perhaps create a damage problem every year or at best, be unpredictable in their feeding attacks. If this is the case, strategic timing of spacing operations may not help reduce or eliminate damage. Therefore, an intensive long-term study of squirrel population dynamics and feeding injuries in control and spaced stands was initiated in the Cariboo and Prince George Forest Regions of B.C. in 1981.

In general, squirrels damage larger crop trees and remove greater amounts of bark per attack than do hares (fig. 4). Squirrels tend to attack stems which are larger than 60 mm dbh. Damage intensities in spaced stands have generally declined from 1980 (range of 32.0 to 56.7%) to 1983 (range of 0 to 20.0%)

as have population densities of squirrels (Sullivan, T. P. and A. Vyse, in preparation). To date, bark and cambium removal by squirrels has not had an adverse effect on 3-year diameter increments. However, it must be stressed that these rodents appear to attack the large diameter (and presumably faster growing and perhaps more nutritious) crop trees in a thinned stand. Since damage by snowshoe hares to small ($<$ 60 mm dbh) trees clearly suppressed diameter growth, firm conclusions should not be drawn regarding the impact of bark and tissue loss on large ($>$ 60 mm dbh) trees until more growth response data become available.

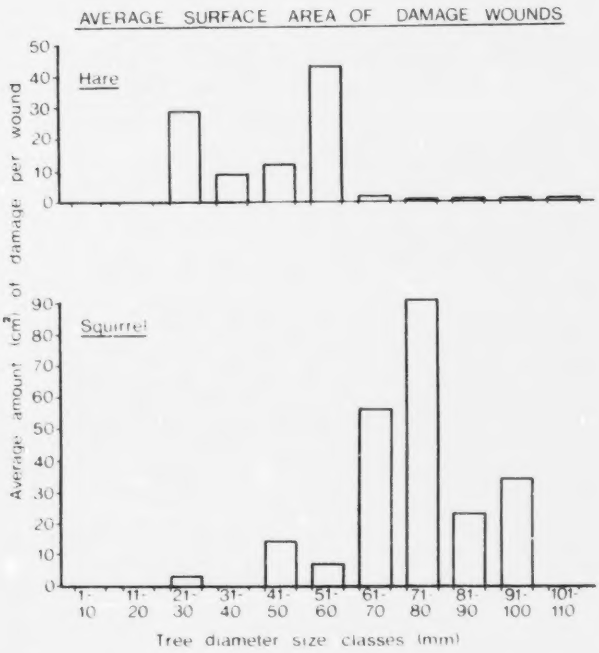


Figure 4. – Comparison of hare and squirrel-attacked lodgepole pine crop trees and the average amount (cm^2) of damage (bark and vascular tissues removed) per wound.

This apparent lack of an adverse effect due to bark and tissue loss must be treated very cautiously for two reasons. An impact on growth may not become obvious for several years, either because additional wounds may reach a threshold level resulting in physiological stress, or wounds may act as entrance courts for disease or parasites. Hare damage occurs during the winter and into early spring when fungal and related parasites may not be prevalent. Alternatively, the spring to early summer period of squirrel damage may be more harmful to a given tree because of the seasonal synchrony of parasites and damage. The economic significance of decay in the wounds incurred from logging and fire has been reported by several authors (Molnar and McMinn 1960; Aho 1977; Etheridge 1978; Filip and Aho 1978). Fungal infection of animal barking wounds may seriously affect lodgepole pine growth and future lumber quality, particularly when they occur so early in the life of a tree. Rundel (1973) has shown the existence of a strong correlation between area of basal fire scars and occurrence of snag tops in mature trees of Giant Sequoia. Similarly, Nordin (1958) for lodgepole pine, and Whitney and Brace (1979) for eastern white pine (*P. strobus*) have outlined the importance of fungi entering damage wounds and their adverse effect on lumber quality.

Interim Recommendations to Alleviate Damage

Since lodgepole pine crop trees may not outgrow susceptibility to squirrel attack, as is the case with snowshoe hares, a diameter-specific spacing strategy coordinated with low squirrel populations is not a viable recommendation. However, the 2-step spacing program discussed for snowshoe hares may be adapted for squirrels, if and only if, stems have grown beyond susceptibility before the stand undergoes the second stage thinning. If squirrel population trends can be elucidated and perhaps related to an environmental factor such as periodicity of cone crops, then some degree of predictability of damage outbreaks might be possible. At such times when squirrels are abundant, a damage reducing strategy may reduce or eliminate damage. For example, provision of an effective repellent system or an alternative food source (sunflower seeds) during the years of high squirrel populations are two potential management techniques.

Porcupines

The porcupine is another animal which removes the bark of lodgepole pine. It leaves broad prominent vertical and diagonal incisor marks on the exposed sapwood (Lawrence *et al.* 1961; Sullivan and Sullivan 1982a). Porcupine damage may be distinguished from the feeding done by squirrels because these latter mammals leave no toothmarks on the sapwood and bark strips (3 x 8 cm) accumulate on the ground under the tree. The majority of feeding by porcupines occurs during fall and winter when herbaceous material is not available. Porcupines are much less abundant (one animal every 10 to 30 ha) than hares (up to 10/ha in peak years of cycle) or squirrels (2 to 7/ha) and so their damage is not prevalent in the lodgepole pine stands of central British Columbia and Alberta (Sullivan and Sullivan 1982a). However, porcupine damage to thinned lodgepole pine crop trees in Utah, 16 years after thinning, resulted in 9 to 26% mortality of crop trees with an additional 10 to 17% damaged (Daniel and Barnes 1959). These animals preferred trees 100 cm dbh or greater which is a similar pattern of feeding attack to that of the red squirrel.

In recent years in Oregon and Washington, porcupine damage has been observed most frequently west of the Cascade Range. Damage by this animal was previously considered a problem throughout much of the pine regions of these states, as well as the southern interior of B.C. However, it is now considered only a minor problem in localized stands (Anonymous 1978).

FERTILIZATION OF JUVENILE STANDS

Snowshoe Hares and Red Squirrels

Damage Assessment

Snowshoe hares and red squirrels cause serious damage to thinned stands of lodgepole pine. However, forest fertilization, which increases the palatability and nutritive value of many plant species utilized by wildlife, may have an impact of even greater magnitude. A study designed to determine the initial incidence of hare and squirrel damage to crop trees in a fertilized-spaced stand compared with those in spaced only and control (unspaced) stands was conducted by Sullivan and Sullivan (1982b).

There was little variation in the percentage of crop trees (range of 53.6 to 63.3%) damaged by hares in the three stands (fig. 5A). However, hares removed significantly more (2 times) bark and associated vascular tissues per attack from fertilized stems than from those in the spaced only stand (fig. 5B). In terms of the average damage per tree, hares removed nearly 3 times the amount of bark and tissue from fertilized stems than from spaced only stems (fig. 5C). More stems in the fertilized stand (10%) were girdled by hares than those in spaced (6.4%) or control 3.9%) stands. Squirrels damaged more fertilized trees (38.9%) than trees in the spaced (30.9%) or control (14.3%) stands (fig. 5A). Again, more trees (6.9%) were girdled by squirrel feeding in the fertilized stand than in either spaced or control stands (0.0%). Squirrels removed the largest average amount of bark (66.9 cm^2) per attack from fertilized stems with little difference between spaced and control stands (fig. 5B). This study concluded that hares and squirrels clearly prefer to feed on fertilized lodgepole pine stems over those in non-fertilized or unmanaged stands (Sullivan and Sullivan 1982b).

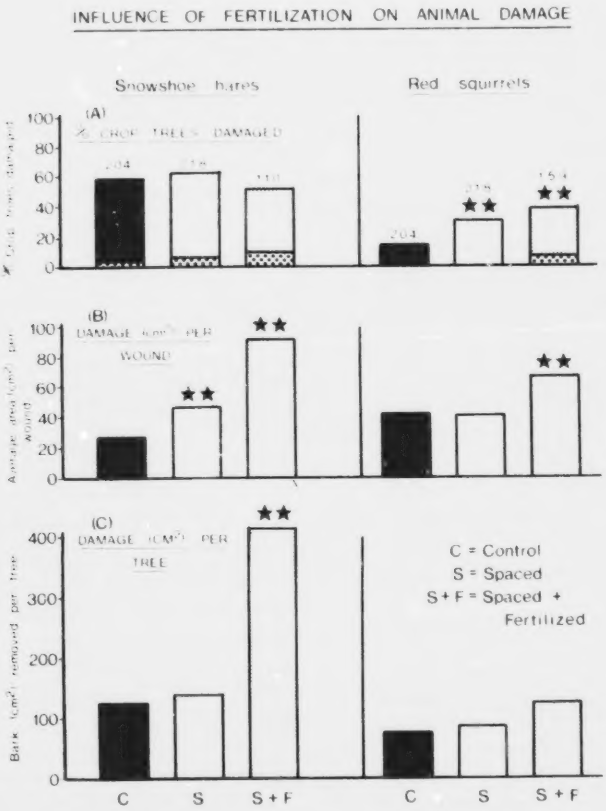
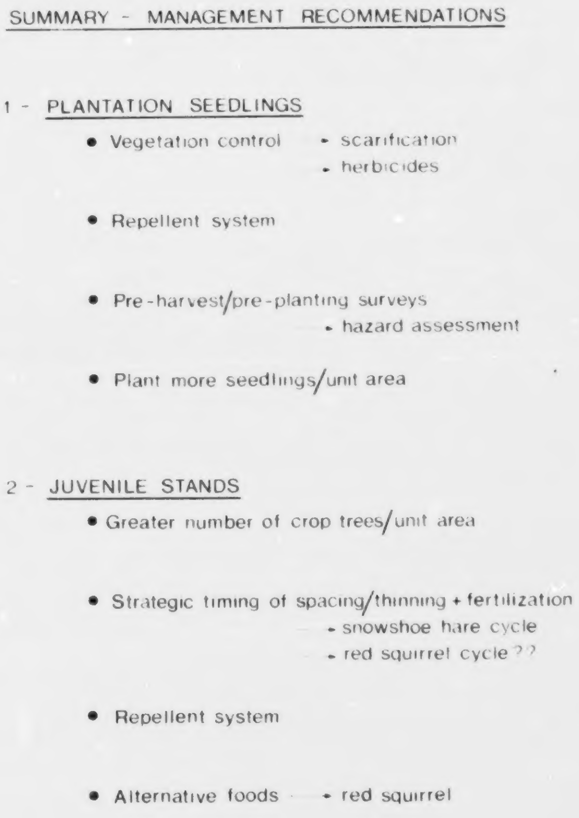


Figure 5.—Influence of fertilization on feeding attacks to lodgepole pine by snowshoe hares and red squirrels. Variables measured included (A) percentage of crop trees damaged, (B) average area of bark and vascular tissues removed per attack, and (C) average area of bark and vascular tissues removed per tree. The large dot shading represents percentage girdled in (A). ** $p < 0.01$ (see Sullivan and Sullivan 1982b).



SUMMARY - MANAGEMENT RECOMMENDATIONS

1 - PLANTATION SEEDLINGS

- Vegetation control
  - scarification
  - herbicides
- Repellent system
- Pre-harvest/pre-planting surveys
  - hazard assessment
- Plant more seedlings/unit area

2 - JUVENILE STANDS

- Greater number of crop trees/unit area
- Strategic timing of spacing/thinning + fertilization
  - snowshoe hare cycle
  - red squirrel cycle ??
- Repellent system
- Alternative foods
  - red squirrel

Figure 6.—Summary of management recommendations to alleviate feeding damage by small mammals to lodgepole pine plantations and juvenile stands.

Interim Recommendations to Alleviate Damage

Silvicultural recommendations to alleviate snowshoe hare damage to fertilized lodgepole pine may be based on those outlined previously for thinned stands. However, further research is required to determine if fertilization increases the diameter-specific susceptibility of lodgepole pine crop trees to hare attack. In addition, crop trees in fertilized stands, which outgrow size susceptibility to hare attack, will still be exposed to squirrel damage presumably for several years. Thus, a repellent system to prevent small mammal feeding on crop trees is clearly a necessary prerequisite to successful thinning and fertilization regimes for lodgepole pine.

The advent of a timed-release biological repellent system would protect intensively managed pole-size stands as well as plantations. Another approach could be the use of fertilizer elements or compounds (in various concentrations and mixtures) which act as a systemic repellent rendering the tree unpalatable to the attacking animal. Selectivity in feeding by both hares and squirrels has been observed in lodgepole pine stands. Therefore, this avenue provides some potential for development of an effective repellent formulation which might also be of value to tree growth and yield.

SUMMARY-MANAGEMENT RECOMMENDATIONS

A summary of management recommendations to alleviate feeding damage by small mammals to lodgepole pine plantations and juvenile stands is illustrated in figure 6.

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INSECTS OF LODGEPOLE PINE: IMPACTS AND CONTROL

Gene D. Amman
and
Les Safranyik

ABSTRACT

Of approximately 240 species of insects that feed on lodgepole pine, 35 are considered pests or potential pests. Nine insect species cause serious damage in periodic, local infestations and one species, the mountain pine beetle, causes catastrophic losses in repeated outbreaks over most of its distributional range. Stand management offers the best possibility for reducing losses. Seed and cone insects do not extensively affect seed production; nursery stock can be protected through cultural practices and pesticide treatments. Several insects affecting young stands cause reduced height growth and permanent crooks in stems. Defoliating insects, such as the lodgepole needle miner and pine sawflies, usually infest trees of all ages and cause growth loss and some mortality during severe outbreaks. Bark beetles, especially the mountain pine beetle, pose the most serious threat to lodgepole pine management.

INTRODUCTION

Lodgepole pine, *Pinus contorta* Douglas, like most trees, provides habitat for a variety of insect species throughout its development. These range from moth larvae that feed on seed and cones to bark beetles that cause widespread mortality of mature trees.

Although we know which insect species most commonly affect different stages of stand development, we lack fundamental knowledge of the significance most insect damage will have on final harvest. The life table approach for forest stands (Waters, 1969) could be used for an integrated analysis of forest stand productivity and an assessment of important agents affecting productivity, including insects.

Generally, insects affect productivity in four ways, as illustrated by the following examples:

1. *Understocking.* – Even though large amounts of seed are produced and large numbers of seedlings emerge, insects that destroy seed and seedlings can reduce productivity; losses during early stages of stand development can result in an understocked stand at the time of tree harvest. (fig. 1A).
2. *Reduction in merchantability.* – Insects that kill terminal leaders can cause deformed or multistemmed trees that yield less merchantable wood at time of tree harvest. Following harvest, merchantability can be further reduced by insects that bore holes into the wood unless logs are processed promptly (fig. 1B).
3. *Growth reduction.* – Insects that remove large amounts of foliage or those that partially girdle trees reduce growth and productivity because a longer time is required for a tree to reach merchantable size (fig. 1C).
4. *Direct killing.* – Bark beetles cause large losses in productivity by killing merchantable trees and by reducing numbers of merchantable trees to the point that harvest of residual trees cannot be accomplished profitably (fig. 1D).

As the intensity of forest management changes, insect problems will change also. This fact is already apparent; several insect species previously considered to be innocuous under natural stand conditions have caused extensive damage when planting and thinning were attempted.

Insect species have been divided into groups that affect the different stages in the life of lodgepole pine trees. Only some of the more important species have been included. Nursery pests are not treated. These usually are general feeders and are covered in publications such as Sutherland and Van Erden (1980). The greatest effort has been placed on the mountain pine beetle because of interest generated by severe, almost continuous losses of lodgepole pine during the past 25 years. For more detailed descriptions and life histories and for broader coverage of insect species affecting lodgepole pine, you are referred to Furniss and Carolin (1977) and Evans (1982). Recommendations for control of insects by chemical insecticides are avoided purposely. Recommendations for use of pesticides change; some are no longer in effect, whereas improved materials and methods are being developed.[1]

INSECTS OF REPRODUCTIVE STRUCTURES

Although animal and weather factors may destroy a large proportion of lodgepole pine reproductive structures some years, these losses have a negligible silvicultural effect (Tackle, 1961). Studies of red pine cones suggest destruction of developing cones by insects may actually enhance flower primordia production and, consequently, the abundance of future feeding and breeding sites for cone insects (Mattson, 1978).

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[1] Insecticides used for direct control or preventive sprays are reviewed continually by the Environmental Protection Agency. Therefore, persons contemplating use of insecticides should ensure that the materials are currently registered for use.

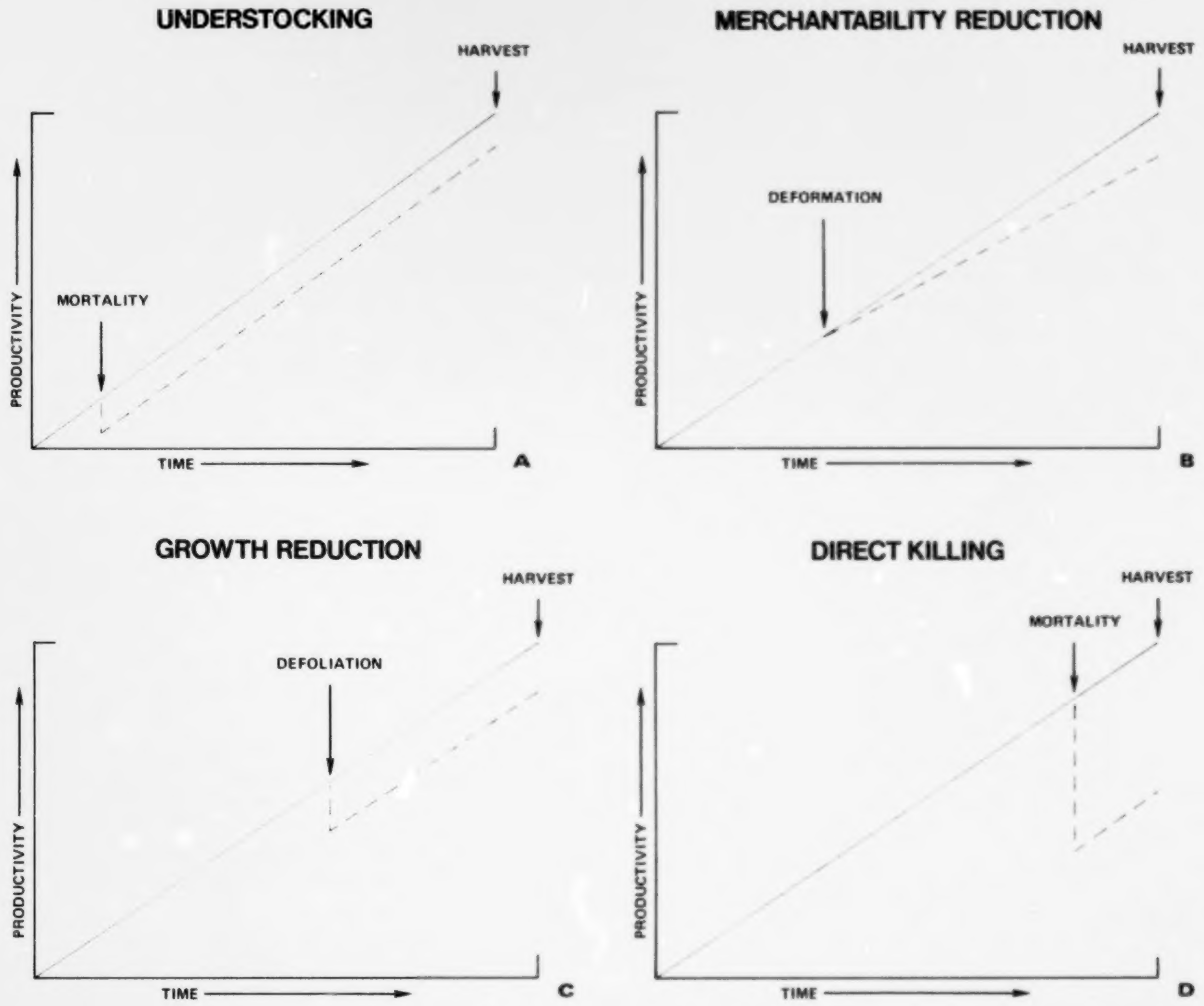

Figure 1.–A. Effect of stand understocking on productivity. B. Effect of reduction in tree merchantability on productivity. C. Effect of tree growth reduction on productivity. D. Effect of merchantable tree mortality on productivity.

The closed-cone habit of lodgepole pine is at least partially responsible for the negligible effect of losses. In stands of lodgepole pine where the closed-cone habit prevails, millions of viable seed may be stored per hectare for many years (Lotan and Jensen, 1970). Following fire or cutting, this seed then is available for seeding the area. In stands where the closed-cone habit is limited, however, seed losses to insects could have a significant effect on attempts to generate some stands. In addition, some of these insects could become major factors when superior tree and seed selection programs for lodgepole pine are initiated.

Since the Lodgepole Pine Symposium in 1973, a number of additional species have been reported feeding on the reproductive structure of lodgepole pine (Furniss and Carolin, 1977), and perhaps the reason damage has been considered low (Keen, 1958) is that few studies of only short duration have been conducted. A study of lodgepole pine cones in 1971 found only 2 percent infested by insects (Parker, 1972). Larvae of the moths (Lepidoptera) are the most common insects infesting lodgepole pine reproductive structures.

Lodgepole pine cone borer, *Eucosma rescissoriana* Heinrich (Lepidoptera: Olethreutidae), larvae tunnel in second-year cones and feed on the scales and seeds, consuming the softer parts of cones, leaving the woody veins and paper-thin layers at the surface of the cone scales. Larval mines are packed with fine-grained dark brown frass pellets. Damaged scales may fail to open at cone maturity, trapping sound seed within the cones (Hedlin *et al.*, 1981). The proportion of damaged cones is usually low, but is found to increase with spacing in western white pine plantations in Idaho (Ollieu and Schenk, 1966).

The adults, which have tan forewings with rust-red markings, emerge and lay eggs on cone scales. Larvae hatch from the eggs in about a week and tunnel between cone scales into the seed, where they feed on seeds and scale tissue. The dirty white larvae may damage more than one cone in completing development (Hedlin *et al.*, 1981). They drop to the forest floor to spin cocoons and pupate in September and October. There the pupae overwinter and development is completed in the spring.

Laspeyresia toreuta (Groté), one of the seedworms (Lepidoptera: Tortricidae), is associated with seed, upon which the larvae feed almost exclusively. Cones of pines are infested during the second year of development. The cones show no external evidence of damage. Upon hatching, the larva bores between cone scales, enters a seed, and consumes it, then moves on to the next seed, leaving frass and a silk-lined tunnel. When fully developed, the cream-colored larva tunnels into the cone axis, where it overwinters. In the spring, development is completed and the adult emerges to lay eggs on the cones (Fig. 2) (Hedlin *et al.*, 1981).

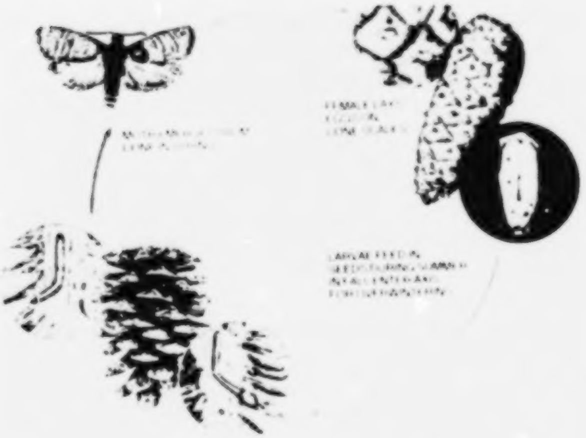

Figure 2.–Life cycle of a seedworm, *Laspeyresia* sp. (Hedlin *et al.*, 1981).

Dioryctria abietivorella (Groté), the fir coneworm, feeds on the cones of lodgepole pine, leaving conspicuous frass and webbing on cone surfaces. Boring larvae riddle the cones. Some larvae pupate in the ground in late summer; adults emerge shortly after to lay eggs which overwinter. Other larvae overwinter in cocoons, then complete development in the spring. Adults emerge and lay eggs in May and June (Hedlin *et al.*, 1981).

The reproductive structures of lodgepole pine are a major feeding site for larvae of *Choristoneura lambertiana* subspecies *subretiniana* Obraztsov (Lepidoptera: Tortricidae), one of the budworms (Stark and Borden, 1965). Cones are often completely excavated.

When the budworm larvae hatch in late summer, they may feed on the needles, and defoliation is the most conspicuous indicator of the insects' presence. But, if male and female flowers and cones are present, those may be preferred feeding sites. External frass and webbing are signs of infestation. Flowers may be completely consumed and holes bored into the developing cones (Hedlin *et al.*, 1981).

Adults emerge in mid-to-late summer and lay eggs that are flattened and overlapping in long masses on the needles. When the larvae hatch in late summer, they molt once, without feeding, and overwinter in small webbed tents called hibernacula. In the spring, the larvae mine old needles or buds and flowers. Then they feed on new foliage and in some cases the cones. Pupation occurs on the tree about midsummer.

The ponderosa pine cone beetle, *Conophthorus ponderosae* Hopkins (Coleoptera: Scolytidae), considered potentially the most damaging insect in seed orchards and seed production areas (Dale and Schenk, 1978), also feeds on lodgepole pine cones. Second-year cones are attacked in late spring or early summer by adult female beetles, severing conductive tissue at the cone base. Dead cones appear as shriveled brown cones on the tree or as partly developed cones that fall to the ground. The beetles enter through the cone stalk or side of the cone near the base. Eggs are laid in a gallery made in the cone. Larvae complete development in about a month, pupate, and then become adults. The adults may overwinter in the dead cone, or leave and enter shoots or conelets where they feed and overwinter. A single generation is produced each year.

The western conifer seed bug, *Leptoglossus occidentalis* Heidemann (Hempitera: Coreidae) feeds by piercing the cone scales into developing seeds. When feeding occurs before the seedcoat hardens, the contents of the seed are removed and the seedcoat collapses. If the seedcoat has hardened, the seedcoat does not collapse (Krugman and Koerber, 1969), even if the contents have been removed. When adults first emerge from hibernation in the spring, they feed on developing male flowers, causing them to be stunted or deformed. The pollen sacs are pierced and pollen dissolved, causing necrotic areas around the feeding site and thus reducing pollen production.

The bug has one generation per year, laying eggs on needles. When nymphs hatch from eggs in May to early July, they feed upon developing cones and seeds. The nymphs mature by August but continue to feed on seed until cold weather arrives, when they seek sheltered locations for hibernation.

Xyela alberta (Curran), the pine catkin sawfly (Hymenoptera: Xyelidae), feeds in developing male flowers. The flowers may be obviously deformed by effects of oviposition and flecked with resin. Larvae feed on pollen, moving from sac to sac. When grown, they drop to the soil where they pupate, remaining there for one to two seasons (Hedlin *et al.*, 1981). The pine catkin sawfly probably is not of much importance in the forest; however, they could reduce pollen significantly from particular clones used in artificial breeding.

INSECTS OF SEEDLINGS AND SAPLINGS

Some of the insects mentioned in this section also can extensively damage pole and mature trees. Likewise, some insects mentioned in the section dealing with pole and mature trees can damage younger trees. For convenience, discussion is limited to the period in the life of the tree when damage is likely to be most significant.

Previously, damage by insects that affects young trees has been considered of little economic importance, but Fellin and Schmidt (1966) warn that this type of damage can be expected to increase as forest plantations and naturally regenerated stands increase in acreage. Recent observations of damage in young lodgepole stands throughout much of the lodgepole pine type gives credence to their statement. The principal problem presented by insects affecting young trees is the killing of the terminal, which may result in a crooked or multistemmed tree and a reduced amount of merchantable wood at maturity. In addition, insects can have a devastating effect on lodgepole grown for Christmas trees.

Shoot Insects

The lodgepole terminal weevil, *Pissodes terminalis* Hopping (Coleoptera: Curculionidae), occurs throughout the range of lodgepole pine and probably is the most important insect affecting young lodgepole. In Alberta, weevils are most common in the central and southwestern regions (Johnson *et al.*, 1971). Adult weevils usually feed and oviposit in elongating terminal leaders during June and July. The current year's terminal growth is killed when larvae mine through the phloem, sapwood, and pith (Salman, 1935; Stark and Wood, 1964). Occasionally, lateral terminals are infested. Infestation causes reduced height growth, permanent crooks in stems and, in severe cases, "stag-headed" crowns.

Larvae usually complete development by late August and overwinter in the shoot (Stevens and Knopf, 1974). Some individuals overwinter as pupae (Evans, 1982), however, while others develop to adults and emerge in the fall (Stark and Wood, 1964; Drouin *et al.*, 1963). These adults may overwinter in the forest floor. Overwintering larvae complete development in the spring and emerge in June and July, completing the single generation per year.

Large percentages of trees in some stands have been infested at one time or another; for example, in two stands in Idaho, 50 percent (Stevens and Knopf, 1974) and 80 percent (Klein and Tegethoff, 1970) of the trees had been infested, and in two stands in central British Columbia, 40 percent and 50 percent top kill occurred (Johnson *et al.*, 1971). Stevens and Knopf (1974) felt that fairly heavy weevil activity could be tolerated in stands managed for poles and sawlogs because severely damaged trees could be removed in thinning at age 30. After age 30, very little weevil infestation occurs. In addition, most trees outgrow the effects of weevil infestation.

Salman (1935) wrote that terminal-feeding weevils do less well under shaded conditions. Attacks are most commonly confined to the leaders of vigorously growing trees, and maximum damage occurs in open stands 1.5 to 5.0 m (5 to 16 ft) high (Drouin *et al.*, 1963; Stevenson and Petty, 1968). Significantly higher damage levels occur in thinned than unthinned stands of lodgepole pine (Bella, in press). Nevertheless, Stevens and Knopf (1974) did not believe that the weevils preferred open stands. These differences in weevil response may be related to geographic location. Additional work is needed to determine if controlled stand density would be worthwhile in minimizing damage by the terminal weevil. The degree of shading through controlled stocking will be a compromise between stocking that yields rapid growth and stocking that reduces weevil damage to an acceptable level. Weevils in Christmas tree plantations would probably require control by chemical insecticides.

The western pine shoot borer, *Eucosma sonomana* Kearfott (Lepidoptera: Olethreutidae), also infests the shoots of lodgepole pine. Although the effects of shoot moths on lodgepole have not been assessed, loss in average annual height increment of infested ponderosa pine is estimated at up to 25 percent of height increment for uninfested trees (Stoszek, 1973).

Moth activity on lodgepole pine is probably similar to that reported on ponderosa pine. The shoot moths lay eggs in early spring, with larval hatch occurring with start of bud elongation. Larvae bore into the pith of expanding buds, the shoot apex apparently being preferred. The feeding tunnel is confined to the pith region; it is straight and filled with compacted frass (fig. 3). Mature larvae leave the shoot, drop to the soil, and pupate. More infested leaders occur on dry sites than wet sites. No control is recommended at this time. Additional work is needed on shoot borer damage in lodgepole pine.

The European pine shoot moth, *Rhyacionia buoliana* (Schiffermuler) (Lepidoptera: Olethreutidae), is potentially one of the most damaging shoot-boring insects of lodgepole pine. This introduced species now is established in various locations in British Columbia, Washington, and Oregon, mostly on ornamental and shelterbelt pine trees (Harris and Ross, 1973; Furniss and Carolin, 1977). Naturally growing lodgepole pine are also susceptible to damage. Trees from seedling size to about 7.5 m (25 ft) tall are most susceptible to injury. Damage is caused by the larvae mining the buds and shoots. Trees are most seriously affected when the terminal shoot is infested, resulting in reduced height growth and forked, multiple, or crooked stems. Young trees are sometimes killed.

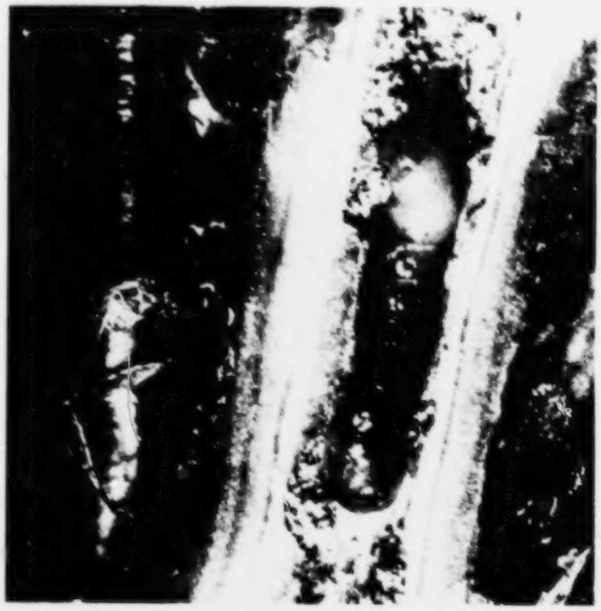

Figure 3. – Terminal shoot of lodgepole pine is killed by *Eucosma sonomana* larva feeding within the shoot.

The European pine shoot moth has one generation per year. Adults moths fly in midsummer (active at dusk), and eggs are laid on twigs, buds, and needles. Larvae mine into nearby needles and later move into buds to overwinter. The following spring, the dark brown larvae mine buds and new shoots, reaching 10 mm (0.4 inch) in length when mature. Pupation occurs in a mined shoot about mid-May (Evans, 1983; Furniss and Carolin, 1977).

The distribution of the moth is generally limited above snowline by minimum temperatures of -29°C and lower. Prevention of the movement of infested stock, coupled with control of local infestations, are the most effective measures in containing the spread of the insect into uninfested areas. Insecticides are effective when applied April to mid-May to kill active larvae, and mid-June, after egg hatch and before the larvae burrow too deeply into buds. In addition, clipping and burning of infested shoots in gardens and nurseries help prevent the spread of infestations.

Pine gallmidges, *Cecidomyia* spp. (Diptera: Cecidomyidae), are widely distributed throughout the range of lodgepole pine. Several types of damage are described from British Columbia (Evans, 1983): crooked shoots occur principally on lodgepole pine, and twig swelling and pitch blisters occur mainly on shore pines. Damage is most commonly associated with young trees and frequently occurs on leaders.

The adults are fragile insects, approximately 2 to 5 mm (0.08 to 0.20 inch) long, have nearly clear wings, and resemble mosquitoes. Their coloration varies from pale brown to pink and black, depending on species and sex. Eggs are pink or brown, and the larvae and pupae (about 2.5 mm = 0.1 inch long) are pinkish-orange when mature. Adults fly during late spring and the females lay eggs on the scales of young shoots. Larvae bore into the plant tissues, feed, and overwinter there.

Crooked shoots are caused by larvae feeding inside the ends of needles near the bases of shoots. More than 40 percent of the shoots on a tree may be affected (Evans, 1983), and shoot mortality is about 12 percent. Twig swelling, which occurs mainly in pine reproduction, is caused by larval feeding in pitch blisters in the bark of last year's leader growth. The feeding activity causes swelling of the shoot and frequently is followed by mortality.

Outbreaks by *Cecidomyia* spp. in young lodgepole pine stands developed in four areas in the Prince Rupert Forest Region of British Columbia during 1972-73. Up to 40 percent of the leaders were killed. Control has not been attempted.

Stem Insects

A weevil, *Hylobius warreni* Wood (Coleoptera: Curculionidae), has caused extensive damage to lodgepole pine, attacking healthy trees from a few years old to maturity. Adult weevils feed on terminal shoots and needles and cause negligible damage. Larvae feed on phloem and cambial tissues, however, girdling roots and portions or all of the root collar, which causes reduced radial and height increments (Cerezke, 1972) or kills the tree (Warren, 1956a). Wounds may serve as entry points for root and stem diseases (Cerezke, 1971).

Tree mortality is most common in stands less than 30 years old. Weevil attack preference was found to be directly related to tree size and age and the thickness of the duff, and inversely related to stand density (Cerezke, 1970). The highest weevil populations tend to occur on the better pine sites at lower elevations. A method for estimating abundance of the weevil and its damage has been developed (Cerezke, 1970). In natural stands, the kill rarely exceeds 5 percent (Cerezke, 1974). In eastern Canada, pine plantations tend to be more heavily attacked (up to 63 percent mortality) than natural regeneration (Cerezke, 1971). In artificially regenerated lodgepole pine stands, weevil impact has not been adequately assessed. In one study from central British Columbia, estimated mortality from the root collar weevil in eleven 7-year-old plantations ranged from 2 to 13 percent (Herring and Coates, 1981).

H. warreni lays eggs in small niches chewed in the outer bark at the base of main lateral roots of healthy pines. The young larvae feed in the living phloem and cambium of the root-collar zone below the surface of the forest duff. They pupate in chambers composed of bark and humus. Up to 2 years may be required to complete development. Silvicultural methods offer the best opportunity for control of *H. warreni.* Weevil damage is more common on wet sites than on dry sites (Warren, 1956b) and year-to-year damage is correlated within weevil-infested stands, an indication that certain stands are subject to continual infestation (Cerezke, 1970). Nonhost trees could therefore be grown on susceptible sites. Pines appear to be preferred hosts, although white spruce is readily infested also (Warren, 1956a).

In the process of reforestation, logging debris should be burned or removed, including all advanced pine and spruce regeneration. Cerezke (1971) noted that clearcutting in large blocks, followed by scarification, will probably provide control of the weevil and prevent damage to regeneration in the clearcut blocks. Weevils have a high moisture requirement (Warren, 1956a; 1956b), so trees in the new stands that have a layer of moist humus at their bases are more subject to infestation.

The pitch nodule moth, *Petrova albicapitana* (Busck) (Lepidoptera: Olethreutidae), is distributed throughout the northern States and in Canada. In Alberta, the moth is most common at elevations less than about 900 m (2,953 ft) (Drouin, personal communication, 4/84). This insect usually attacks young lodgepole pine to the sapling stage, but it is also common on mature trees. The damage is caused by the larvae feeding on the bark, phloem, cambium and, to a lesser extent, on the sapwood of both the new and old growth of stems, twigs, and branches. Larval presence is recognized by nodules of pitch and frass where the larvae entered the bark (fig. 4). Attacks usually are at nodes or whorls of branches. These weakened portions frequently are broken by wind or snow (Keen, 1952; Drouin and Kusch, 1981).

The pitch nodule moth requires 2 years to complete its life cycle. Eggs are laid on needles or at the base of the needle sheath from early June to mid-July. The larvae feed in the terminals, creating small circular excavations in the cortex. These are covered with silk and pitch. As they feed, larvae create nodules. With the onset of cold weather, larvae become dormant. In spring, larvae leave the overwintering nodules and move along branches toward the tree trunk. Larvae resume feeding at crotches on the main stem or on a branch, forming new nodules about 2 cm (0.8 inch) in diameter. The larvae spend the second winter in these nodules. In early spring, the larvae feed a short time, then pupate. Adults emerge in June to mid-July (Turnock, 1953).

Trees between 0.3 to 1.5 m (1 to 5 ft) tall are most susceptible to infestation. A significantly higher percentage of trees are damaged in thinned than unthinned lodgepole stands (Bella, in press).

Nurseries and Christmas tree plantations may require protection with chemical insecticides. Control of 67 to 71 percent was achieved during a test of dimethoate used as a soil drench (Drouin and Kusch, 1981). No chemicals are registered for control of the pitch nodule moth.

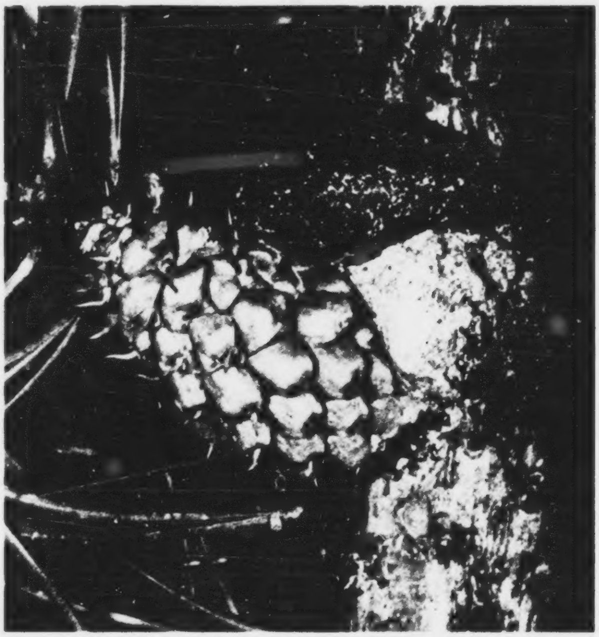

Figure 4. – Pitch mass is formed during feeding by pitch nodule moth larva, *Petrova* sp. Stems are weakened and subject to wind breakage. Courtesy H. F. Cerezke.

Another moth, the sequoia pitch moth, *Synanthedon sequoiae* (Hy. Edw.) (Lepidoptera: Sessidae), was reported to be a pest of lodgepole pine as early as 1914, when serious infestations occurred over 36,422 ha (90,000 acres) of lodgepole pine in Montana (Brunner, 1914). Larvae usually feed around the root collar or near the base of branches. Larval feeding in the cambium causes massive pitch flow (fig. 5), growth reduction, and even death of some trees. The lack of frass particles in the pitch helps distinguish pitch moth infestation from that of bark beetles. The pitch moth prefers open stands and dry, sunny slopes. The life cycle requires 2 years. The adult moths are black with yellow markings, and have clear wings with a span of 25 to 30 mm (1 to 1.2 inches). The moth, which resembles a hornet, lays eggs on the trees during early summer. Eggs hatch and larvae enter the bark before winter. The larvae overwinter twice, pupating in late spring of the second year of the life cycle. An outbreak of the insect in over 400 sapling-size pines near Trout Creek, Mont., was associated with pruning and thinning operations; many trees were nearly girdled at the root collar (Tunnock, 1967). Pruning for fuel breaks in California attracted the sequoia pitch moth, which infested mostly the largest, most vigorous trees (Powers and Sundahl, 1973). The large resin masses associated with infestation are deemed a hazard when using prescribed fires to maintain a fuel break because they readily ignite. Adverse appearance of *S. sequoiae* attacks affects the esthetics, particularly along roadsides (Powers and Sundahl, 1973). Pruning and thinning after moth flight so moths are not attracted probably would result in less infestation.

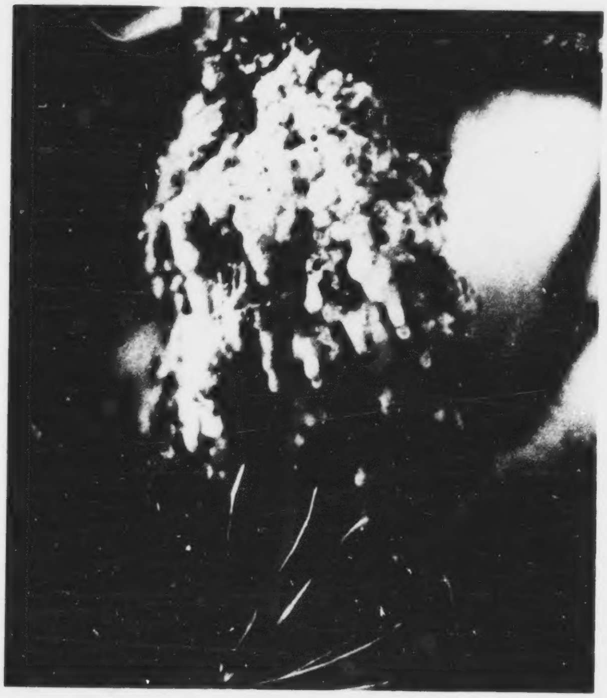

Figure 5.—Feeding in the bark by larvae of sequoia pitch moth, *Synanthedon* sequoiae, causes large pitch masses to form and may completely girdle trees.

Needle Insects

Adults of the weevil, *Magdalis gentilis* LeConte (Coleoptera: Curculionidae), make feeding punctures that cause defoliation of young trees; the adults are attracted to stands being thinned. Habits of larvae are unknown. Damage to young trees is most severe when thinnings are made prior to late July; therefore, conducting thinning operations after July, when adults are not present to be attracted into the thinning, should help reduce damage (Hamel and McGregor, 1974). Denser stocking could also reduce damage; more weevil damage occurred where trees were widely spaced (Fellin and Schmidt, 1966; Fellin, 1973).

Sucking insects (Homoptera: Diaspididae) commonly found on lodgepole pine are the pine needle scale, *Chionaspis* (*Phenacaspis*) *pinifoliae* (Fitch), and the black pine leaf scale, *Nuculaspis* (*Aspidiotus*) *californicus* Coleman. In Canada, areas where repeated infestations occurred are the Okanagan and East Kootenay of British Columbia. In the United States, notable infestations occurred at Cashmere and Spokane, Wash.; The Dalles, Oreg.; and several areas in California. The pine needle scale is usually a pest of young trees in low vigor. Nevertheless, a severe infestation developed on 500 ha (1,236 acres) of mature trees near Lake Tahoe, Calif. (Pierce, 1969). On severely infested trees, foliage turns yellow or becomes mottled and eventually drops from the tree. Infestations cause growth loss and may gradually kill branches and sometimes the entire tree.

Young pine needles scales are pale brown and about 1 mm (0.04 inch) long; the scale covering the mature, wingless female is white, flat, narrow, and about 3 mm (0.12 inch) long. They occur on needles and stems. In the cold interior climate, the scale overwinters only as eggs, but in the warmer maritime climate, both eggs and adults overwinter. Eggs overwinter under the body of the female and in the spring hatch into briefly mobile nymphs. Usually there is one generation a year (Evans, 1982).

The black pine leaf scale is commonly associated with the pine needle scale. The black scale (about 2 mm = 0.08 inch long), as its name implies, is black or dark grey and easily distinguished from the pine needle scale, which has a whitish covering. There may be one or more generations per year. This scale is usually associated with conditions that are harmful to the host tree, such as smog, smoke, dust, and smelter fumes (Edmunds, 1973; Struble and Johnson, 1964).

Both scales can be controlled by insecticides. Spraying is usually unnecessary or impractical under most forest conditions, but may be necessary in nurseries and young plantations. An outbreak of the pine needle scale at South Lake Tahoe was thought related to mosquito fogging that killed parasites and predators which had kept the scale under control (Luck and Dahlsten, 1975).

Actebia fennica Tauscher (Lepidoptera: Noctuidae), the black army cutworm, normally an occasional pest of agricultural crops, is now recognized as a serious pest of newly planted conifer seedlings, including lodgepole pine (Ross and Ilnytzky, 1977). In British Columbia, epidemics occur at about 10-year intervals and major epidemics last up to 4 years.

The black larvae with two double white lines on both sides of the body (fig. 6) are usually seen feeding during May and June and attain a length of about 4 to 5 cm (1.6 to 2.0 inches) upon maturity. In cool weather, the larvae may be active all day but later in the year they tend to hide in the soil during the warmest part of the day and feed mostly at night. Pupation occurs in the soil and, in central British Columbia, the blackish-brown moths, wingspan about 4 cm (1.6 inch), emerge during July and August. Female moths are strongly attracted to new clearings and recently burned areas where they oviposit in the soil. Cutworms overwinter mainly as young larvae.

Complete or nearly complete defoliation of lodgepole pine seedlings usually causes mortality, especially when flushing of the seedlings occurs prior to or during the feeding period of the larvae. The following guidelines (Ross and Monts, 1976) are effective in reducing damage:

1. Do not burn slash on sites to be planted before or during periods of expected or existing cutworm epidemics. A synthetic pheromone is available for trapping male moths for predicting which areas may become infested the following spring.
2. During outbreak years, plant infested sites after June, when cutworm feeding is completed for the year.
3. Treat infested, recently planted sites with an approved pesticide in the spring immediately after larvae become active.

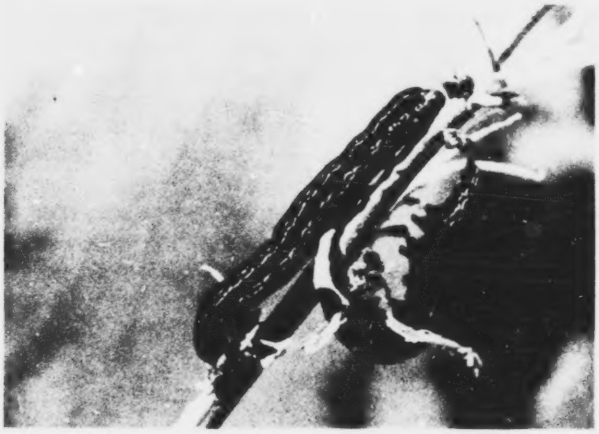

Figure 6.—Larvae of the black army cutworm, *Actebia* fennica, defoliate and kill seedlings.

The spruce spider mite, *Oligonychus ununguis* (Jacobi) (Acari: Tetranychidae), reportedly killed large numbers of lodgepole pine trees in Oregon in the 1930's (Doan *et al.*, 1936). The mites insert sucking mouthparts into the needles to withdraw fluids; injured needles become chlorotic. When populations of mites are large, most needles are killed and the trees die. Outbreaks of this mite have occurred when insecticides were used to control insects (Burke, 1932; Johnson, 1958; Fellin, 1968). Apparently, such natural control factors as parasites and predators of the mite are reduced by the insecticides.

Although miticides for control of mite populations exist, their use is usually unnecessary or impractical under most forest conditions. In nurseries, such outbreaks may require miticidal treatments.

INSECTS OF POLE AND MATURE TREES

At pole stage and beyond, tree loss or reduction in growth is likely to substantially affect stand productivity.

Defoliators

Although defoliating insects occasionally cause widespread mortality, they usually reduce tree growth. Trees are most likely to die when several species of defoliating insects at once eat both old and new needles, resulting in complete defoliation.

Sawflies, *Neodiprion* spp. (Hymenoptera: Diprionidae), are semicolonial defoliators of both young and mature trees. The larvae (fig. 7) feed on old foliage; therefore, damage usually consists of growth loss rather than tree mortality. Occasionally, outbreaks occur over large areas and may last 1 to 3 years. The sawflies derive their name from the toothed lancet used by the female to make an incision in the needle into which an egg is oviposited.

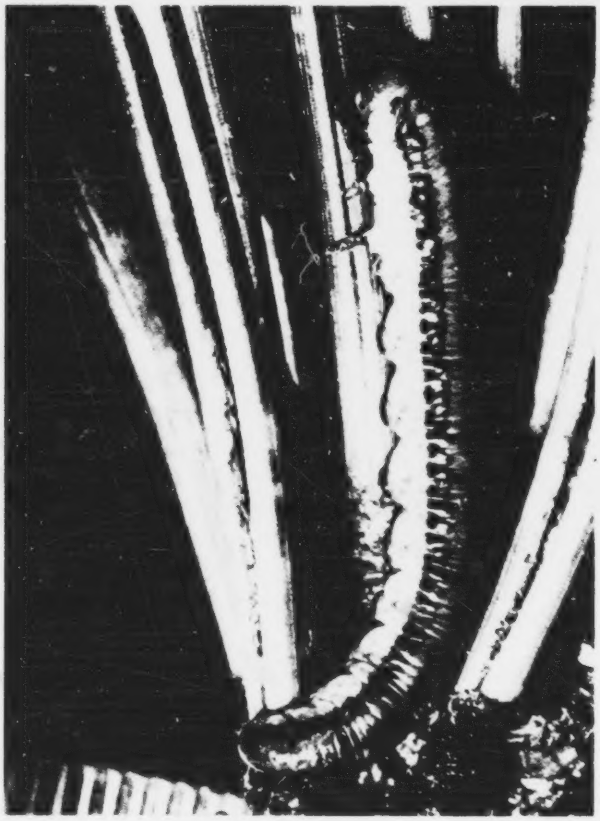

Figure 7.—Sawfly larvae (*Neodiprion* sp.) are common defoliators of lodgepole pine, causing growth reduction.

The lodgepole pine sawfly, *Neodiprion burkei* Middleton, is probably the most frequently encountered sawfly on lodgepole pine. It has one generation per year, but part of each generation remains as prepupal larvae in cocoons on the ground for 2 to 4 years. The sawflies overwinter as prepupal larvae in cocoons in litter on the forest floor. In the spring, development is completed and the adults emerge to oviposit in needles. Larvae usually feed gregariously, consuming most of the needle.

Another sawfly, *Neodiprion nanulus contortae* Ross, also feeds on lodgepole pine, and some tree mortality has been attributed to it. In British Columbia, it is the most damaging of the sawflies (Evans, 1982). This sawfly also has one generation per year, with winter usually passed in the egg stage within the needles, but prepupae may also overwinter. Larvae feed in June and July on old needles. Mature larvae are about 20 mm (0.8 inch) long, have shiny black or brown heads, and longitudinal, shaded green stripes. The mature larvae then drop to the litter and construct cocoons in which they pupate. Adults (6 mm ½ 0.25 inch long) emerge from the cocoons in mid-September to mid-October to lay eggs (Ciesla, 1976).

Most sawfly infestations decline from natural factors before causing much damage. A viral disease was credited with reducing one infestation in Yellowstone Park in 1956 (USDA Forest Service, 1957). However, the large infestation recorded by Burke (1932) indicates the sawfly's potential for damage, particularly when associated with another defoliating insect.

Examples of damage by *Neodiprion* spp. in British Columbia include the outbreaks during the mid-1970's that covered 92,000 ha (227,000 acres) in shore pine on the outer islands near Prince Rupert, and an outbreak of over 9,700 ha (24,000 acres) in lodgepole pine along the Thompson River. The outbreak near Prince Rupert caused considerable mortality after 2 years of heavy defoliation.

Owing to the nature of larval feeding and the short duration of outbreaks, control usually is not required in natural stands, but may be needed in plantations and other high value stands, such as Christmas trees.

The lodgepole needle miner, *Coleotechnites milleri* (Busck) (Lepidoptera: Gelechiidae), and the northern lodgepole needle miner, *C. starki* (Freeman), cause severe defoliation of lodgepole pine during periodic outbreaks in the southern and central Sierra Nevada and the Rocky Mountain Parks region of western Canada, respectively. The most severe outbreaks tend to occur in extensive, mature lodgepole pine stands. Cumulative defoliation by *C. milleri* may cause extensive tree mortality; prolonged defoliation by *C. starki* weakens the tree, but its main effect is growth loss.

Both species have a 2-year life cycle. Adults emerge during midsummer and eggs are laid on the bases of needles. Each larva bores into a needle, feeds, and overwinters there. In the spring, the larva completes excavation of the first needle, emerges, and enters a second needle on new growth and overwinters again. The following spring, the larva enters a third needle, completes development, and pupates (Evans, 1983; Koerber and Struble, 1971). *C. milleri* and *C. starki* fly in odd- and even-numbered years, respectively. The adults are slender moths, light grey to brownish grey, with an average wingspan of about 11 mm (0.4 inch) and strongly fringed hindwings. The mature larva is about 5 mm (0.2 inch) long and has a black head; *C. starki* larvae are dull green; *C. milleri* larvae very in color from yellow to orange, pink, and red (Furniss and Carolin, 1977).

After several successive years of infestation by the miner, trees are weakened and growth essentially stops (Struble, 1973). About 40 percent defoliation is needed before growth reduction can be detected; annual production of new foliage exceeds that consumed by the needle miner when defoliation is less than 40 percent (Stark and Cook, 1957; Cook, 1961). Cumulative effects of defoliation often kill trees. In addition, weakened trees may be attacked and killed by the mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Struble, 1973).

Needle miner populations are usually regulated by weather conditions (Stark, 1959; Struble, 1973). Populations at high elevations and those in valley floors are most likely to be killed because average temperatures are consistently colder than temperatures on midslopes. Also, variation in resistance of foliage to infestation by needle miners was observed in Oregon (Tigner and Mason, 1973). The degree of resistance is probably determined by a feeding deterrent in the foliage.

Direct control of the moths by insecticides proved to be successful and long lasting (Struble, 1973). Larval control was not effective, however, because larvae are protected within needles during most of their development.

Larvae of another small moth, the sugar pine tortrix, *Choristoneura lambertiana* (Busck) (Lepidoptera: Tortricidae), destroy clusters of staminate flowers before new needles develop, and then move to the new needles. Although needles may be destroyed on trees of all ages, sizes, and crown classes within heavily infested areas, trees under 9 m (30 ft) tall appear to suffer heavier damage than larger trees. Larvae usually confine their feeding to new needles on terminal leaders of young trees when populations are small (Stark and Borden, 1965; McGregor, 1968).

Although several years of defoliation may not result in tree mortality, growth reduction can be expected. Feeding during several consecutive years can kill terminals and result in multiforked stems. The life cycle of the sugar pine tortrix was described in the section on insects of reproductive structures.

The lodgepole pine needletier, *Argyrotaenia tabulana* Freeman (Kearf.) (Tortricidae), is another defoliator that occasionally reaches epidemic proportions. For example, an infestation in Idaho covered 40,469 ha (100,000 acres); reproduction and young trees on cutover areas were damaged most severely (Washburn, 1963). The pest's name comes from the larval habit of webbing several needles together to form a tube lined with a papery white web. The larvae feed mostly on the current year's growth (Burke, 1932), maturing in August. They then drop to the ground and spin cocoons in the litter. There they pupate and pass the winter. The adult moths emerge in the spring to lay eggs on the needles.

The rusty tussock moth, *Orgyia antiqua badia* (H. Edw.) (Lepidoptera: Lymantriidae), is a multiple host species and commonly occurs throughout the northern United States and British Columbia. This insect feeds on all native species of pines in its range, but is most commonly found on lodgepole pine.

The adults emerge from mid- to late summer. The flightless female moths deposit eggs (200 to 300 eggs per mass) on their cocoons and winter is spent in this stage. The larvae, which are solitary feeders, complete development during early summer, then pupate in twig crotches and bark crevices. The male moth is rusty brown, has a wingspan of about 25 mm (1 inch) and two white dots on its forewings. The robust female is grey-brown and about 13 mm (0.5 inch) long. the larvae are hairy and strikingly colored; they have a brush of yellow hair in the middle and tufts of black hair at each end of the body. The mature larvae are about 25 mm (1 inch) long.

First signs of defoliation usually become apparent in the upper crowns of trees. Because the females are flightless, large larval populations tend to build up over small areas, causing severe localized defoliation. Rusty tussock moth populations rarely occur at outbreak levels and, when they do occur, are of short duration. Populations collapse naturally from nucleopolyhedrosis virus infection. An outbreak of the rusty tussock moth during 1975-76 in the Monte Hills region of southcentral British Columbia caused moderate to light defoliation over 3,200 ha (7,900 acres).

The need for controlling this insect has not been addressed. It appears that infestation in high value stands should be controlled. Application of nucleopolyhedrosis virus is effective in suppressing tussock moth populations.

The pine needle sheath miner, *Zelleria haimbachi* Busck (Lepidoptera: Yponomeutidae), is a transcontinental species and occurs commonly on lodgepole pine. The larvae are needle miners and defoliators; young trees, up to 5 m (16 ft) high, are infested most commonly. Severe defoliation during localized outbreaks causes growth loss, twig damage, and some tree mortality.

In general, there is one generation per year (Evans, 1982). Adults emerge during early summer to midsummer and lay eggs singly on terminal foliage. The first instar larvae bore into the needle and overwinter. The following spring, the larvae emerge from the needles and feed on new needles, chewing them off near the sheath. Each larva kills several clusters of needles. Pupation occurs during midsummer in silvery webbing in the foliage. The adults are slender, light brown moths with a wingspan of about 11 mm (0.4 inch); the forewings have wide, silvery median streaks. Mature larvae are about 10 mm (0.4 inch) long, slender and tan colored, with dull orange lines on their backs.

Two outbreak periods (1961-62, 1979-80) occurred in British Columbia, both on the Kamloops Forest Region. During 1961-62, from 85 percent to 100 percent of the current growth was destroyed in six areas ranging in size from 40 to 120 ha (99 to 297 acres), and in 1979-80 light to severe defoliation of the current growth occurred in nine areas totaling 5,400 ha (13,344 acres).

The largest of the defoliators that infests lodgepole pine is the pandora moth, *Coloradia pandora* Blake (Lepidoptera: Saturniidae). Adult moths have a wingspan of 7.6 to 11.4 cm (3 to 4 1/2 inches) and larvae are 6.4 to 7.6 cm (2½ to 3 inches) long when fully grown.

Infestations may last 6 to 8 years, cover thousands of hectares, and kill thousands of trees (Wygant, 1941). Infestations occur only about every 20 to 30 years, and can be found only where soils are loose enough to permit pupation of the larvae. Trees die from the direct effect of defoliation after 2 to 3 years; surviving trees show temporarily reduced radial growth. The moth has a 2-year life cycle. Defoliation is light during the first year when larvae are small, and heavier defoliation occurs the second year when larvae reach full size.

Moths emerge from pupal cases in the soil during June and July. Following mating, the blue eggs are laid singly or in clusters on needles, bark, litter, and understory brush. Larvae hatch from the eggs in August and feed in groups on needles at the branch tips until fall, then disperse and feed individually. Larvae overwinter at the base of needles, then resume feeding in the spring. Needles of all ages are consumed. During the last instar, a larva will consume five to eight needle bundles per day. When mature, larvae crawl down the tree trunk and pupate in the soil during July and August (Wygant, 1941).

Natural factors, consisting of predators, parasites, and wilt disease (probably a polyhedrosis virus), usually bring populations under control. A virus was credited with controlling a 6,070-ha (15,000-acre) infestation of the pandora moth in Utah (Washburn, 1962). Tests with the bacterium *Bacillus thuringiensis* offer some promise for control (Carolin and Knopf, 1968).

Defoliator complexes of several insect species are most likely to cause severe loss of foliage. An outbreak of the lodgepole needletier and the lodgepole pine sawfly was especially damaging in the Upper Madison River Valley of Wyoming and Montana from 1921 to 1925. Larvae of the moth fed on current needles; larvae of the sawfly fed on old needles. Almost all trees on 4,856 ha (12,000 acres) were totally defoliated and subsequently died (Burke, 1932). In combination, the insects caused widespread mortality; singly, neither seems to cause extensive tree mortality, but undoubtedly reduces tree growth.

Another complex consisting of the lodgepole needletier, the western spruce budworm, *Choristoneura occidentalis* Freeman (Tortricidae), and the pine needle sheath miner, *Zelleria haimbachi* Busck (Yponomeutidae), caused widespread defoliation in the Intermountain area (Klein, 1967).

Most defoliating insects can be controlled by aerial applications of chemical insecticides. Economic and environmental feasibility of such operations must be carefully evaluated before such control programs are begun.

Bark Beetles

Bark beetles (Coleoptera: Scolytidae) pose the most serious insect threat to growing lodgepole pine. Their capacity to kill trees ranges from that of the secondary beetles, such as *Pityophthorus confertus* Swaine, which can kill an occasional weakened or injured tree, to the mountain pine beetle, *Dendroctonus ponderosae* Hopkins, which can destroy almost all merchantable trees in a stand during a single infestation.

Much has been learned about bark beetles of lodgepole pine, particularly the mountain pine beetle, since the last lodgepole pine symposium 11 years ago. Much of this information has been published (Amman and Cole, 1983; Berryman *et al.*, 1978; Cole and Amman, 1980; Cole *et al.*, in press; Safranyik *et al.*, 1974).

Pityogenes knechteli Swaine and *Pityophthorus confertus* Swaine are two small beetles usually associated with *Dendroctonus* and *Ips* beetles. They frequently are referred to as secondary bark beetles because they usually infest small, stagnated trees that are dying from the effect of tree competition, rather than healthy trees. They also are capable of killing large trees that have been weakened by other causes.

When large infestations of the mountain pine beetle end, secondary beetles that were sustained in the tops and limbs of trees killed by the mountain pine beetle no longer find such material to infest. Consequently, they attack and kill some remaining lodgepole pines (Evenden and Gibson, 1940).

At low population levels of mountain pine beetles, the role of the secondary bark beetles appears to reverse. The secondary beetles kill small-diameter, suppressed, and weakened trees; and the mountain pine beetle follows along, infesting the basal foot or two of the trunks of these trees. Thus, the mountain pine beetle is able to survive during endemic periods. Silvicultural practices that would eliminate at the pole stage trees that are suppressed or weakened by other causes might also eliminate secondary bark beetles and their mountain pine beetle associates from the stands (Richard F. Schmitz, personal communication, Intermountain Forest and Range Experiment Station, Ogden, UT 84401, March 19, 1984).

The bark beetles in the genera *Pityogenes, Pityophthorus,* and *Ips* have one to two generations per year in lodgepole pine, and parents may reemerge and establish a second brood, depending on elevation and latitude. Typically, males of these genera each excavate a nuptial chamber under the bark in the spring. Several females enter the nuptial chamber, where mating occurs; then each female bores a gallery and lays eggs along the sides (Schmitz, 1972; Wood, 1982). The larvae hatch and feed in the phloem tissue. When mature, the larvae pupate and then transform to adults. The adults emerge to start the second generation or drop to the ground, where they overwinter in the litter. When second broods are established, all beetles may not complete development before winter; therefore, larvae and adults may also be found overwintering under the bark.

Ips pini (Say) is a moderately aggressive beetle in lodgepole pine in the Northern Rocky Mountains, but is less aggressive to the south. Most losses attributed to *Ips* occur in conjunction with logging and thinning operations or windthrow and breakage. When slash is not adequate to accommodate the emerging population, standing trees may be infested, especially during warm dry years (Sartwell *et al.*, 1971). *Ips* is less likely to build up after clearcutting than when harvest methods leave standing trees to shade slash. Slash exposed to direct sun dries rapidly. In addition, developing broods may be killed by high temperatures (Reid, 1957). Losses to *Ips* are usually in diameter classes of less than 25.4 cm (10 inches) (Evenden and Gibson, 1940). At high elevations, where mountain pine beetle epidemics seldom occur and, consequently, trees live much longer and grow much larger, *Ips* kills large trees as they become decadent.

Another species, *Ips latidens* (LeConte), occasionally kills lodgepole pine. It usually infests weakened or dying pines, or tops and limbs of mature trees and the boles of pole-size trees. Under favorable conditions, it will kill trees, particularly those weakened by dwarf mistletoe or drought and, in some instances, healthy trees of small diameter.

Losses of lodgepole pine to *Ips* can be minimized best through such preventive measures as removing or burning large slash from logging operations or exposing small slash to direct sun for drying. Control by chemical insecticides usually is not recommended because populations soon decline from natural causes (Sartwell *et al.*, 1971).

The lodgepole pine beetle, *Dendroctonus murrayanae* Hopkins, and the red turpentine beetle, *D. valens* Le Conte, also are considered not very aggressive. They develop in the bases of trees and in freshly cut stumps, but, following cutting operations, may kill some residual trees. In addition, these beetles can weaken trees enough to be killed by other causes, especially other bark beetles.

The adults of *D. murrayanae* and *D. valens* emerge in the spring to infest host material. Attacks are recognized by their large pitch tubes. Characteristics of pitch tubes are related to the vigor of trees infested by each species. *D. murrayanae* infests trees of lower vigor than those infested by *D. valens*. Pitch tubes of *D. murrayanae* are a deep reddish color. They are smaller and contain more boring frass and less pitch than pitch tubes of *D. valens*. Pitch tubes of *D. valens* are more cream color because of the large amount of pitch compared to boring frass they contain. Galleries are made in the bark at the base of the tree and eggs are laid in elongate masses along the sides. Larvae feed side by side in the phloem tissue, killing patches of bark that vary from a few centimeters to more than 30 cm wide. These beetles overwinter as larvae and adults. The number of generations range from one in 2 years at high elevations to three generations at low elevations and southern locations for the red turpentine beetle (Smith, 1971), and from one to one and a half generations for the lodgepole pine beetle. No control of these beetles seems needed, except as described for *Pityophthorus* and *Ips* species to prevent harboring of mountain pine beetles in a stand.

Dendroctonus ponderosae Hopkins, the mountain pine beetle, is the most aggressive bark beetle attacking lodgepole pine (fig. 8). Periodically, it kills most of the large diameter lodgepole pines in a forest before the beetle population subsides. The mountain pine beetle usually has one generation per year. At high elevations where summer temperatures are cool, however, 2 years may be required to complete the life cycle.

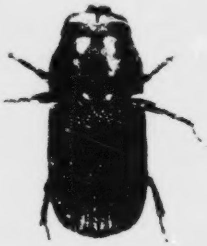

Figure 8. – The mountain pine beetle, *Dendroctonus ponderosae,* kills mature trees and is the most serious threat to growing large lodgepole pine.

All stages are spent under the bark of infested trees, except when adults emerge and fly to infest green trees in midsummer. Eggs are laid along the sides of straight, vertical, frass-packed egg galleries constructed by females. These galleries have a slight hook at the base and are mostly in the inner bark, but slightly score the sapwood. Galleries average about 25 cm (10 inches) long.

Larvae feed on the inner bark (phloem), constructing galleries that extend approximately at right angles to the egg galleries. Larvae overwinter and are very cold hardy. When fully developed, larvae excavate oval cells where they transform into pupae. Normally, pupae transform into adults by July, and adults usually leave the tree in late July and early August to infest green trees.

If the mountain pine beetle attacks are to be successful, the attacking insects, with their associated blue-stain fungi, must be present in sufficient numbers to overcome resistance of the tree. The mountain pine beetle uses a complex of three behavior-modifying chemicals, one a host tree monoterpene, Myrcene, and the other two are the insect-produced trans-verbenol and exo-brevicomin, to mediate mass attacks on host trees (Borden *et al.,* 1983). This process results in sequential colonization of nearby host trees and expansion of the infestation about the tree(s) which became attacked first. When beetles are not present in sufficient numbers, or when resistance is too high, trees may "pitch out" the beetles as they bore into the inner bark, or resin kills the eggs after galleries are made.

The blue-staining fungi that mountain pine beetles introduce into the trees at the time of attack form an integral part of the beetle's ecology (Shrimpton, 1978). Adults carry the spores on their bodies and in a special cavity inside their mouths. In successfully attacked trees, blue-stain fungi colonize and kill living tissues. This results in cessation of resin flow and, together with mining of the inner bark by beetle larvae, soon kills the trees.

Response to artificial inoculations of the fungi show that tree resistance reaches a maximum at the beginning of July and then decreases. Interestingly, the attack period of the beetle during late July and early August corresponds with decline in seasonal resistance (Reid and Shrimpton, 1971). Trees that are resistant to fungal inoculation have the fastest growth rate and the thickest phloem (Shrimpton, 1973). Paradoxically, these are the trees the beetle must overcome in order to increase or maintain large populations, beetle production being directly related to phloem thickness.

The first indication of beetle-caused mortality is usually discolored tree foliage. Needles on successfully infested trees start to fade and change color several months to almost a year after beetle attack. The sequence of color change is green to yellowish-green, then sorrel, red, and finally rusty-brown.

The mountain pine beetle is food limited in those stands of lodgepole pine where developmental temperatures are optimum. Only trees that have a phloem thickness of about 2.5 mm (0.1 inch) usually produce enough beetles to keep an infestation going. When beetles have killed most of the trees that have thick phloem, they attack smaller trees that have thin phloem and that dry excessively during beetle development. Consequently, beetle survival is low and the population declines. At high elevations and more northerly latitudes, populations are weather regulated (Safranyik *et al.,* 1975; Thomson *et al.,* in press).

Phloem thickness is highly correlated with tree diameter within any given stand. This strong correlation is probably involved in the beetle's behavior of selecting greater proportions of the large than small diameter trees. For each increase of 2.5 cm (1 inch) in diameter, Hopping and Beall (1948) showed a 5 percent increase in mortality in stands near Banff, Alberta, and Roe and Amman (1970) showed an increase of 8.8 percent on the Teton and Targhee National Forests in Wyoming and Idaho. Mortality ranged from about 1 percent of the trees 10.2

cm (4 inches) diameter at breast height (d.b.h.) to about 87 percent of those 41 cm (16 inches) and larger d.b.h. (Cole and Amman, 1969); however, tree losses very considerably with elevation. Frequency of infestations on a given area of forest appears to range from 20 to 40 years.

During low population levels (endemic), mountain beetles are difficult to find. They, as previously mentioned, have been found associated with secondary bark beetles in pole-size and larger trees. Just how the transition from endemic to epidemic populations occurs is unknown. Before an outbreak can occur, however, certain stand conditions conducive to buildup of beetle populations are essential. Those that have been identified for natural lodgepole pine stand are: (1) average diameter greater than 20.3 cm (8 inches) for trees 12.7 cm (5 inches) and larger d.b.h.; (2) average age about 80 years or older; and (3) climatic suitability for beetle development.

Several theories exist for the transition from endemic to epidemic populations in stands having these conditions. One theory is that stress of the trees or stand is necessary because the small numbers of beetles produced during endemic levels are unlikely to kill a vigorous tree in which beetle production would be large enough to start an epidemic (Berryman, 1978). A second theory is that small numbers of mountain pine beetles produced in association with secondary bark beetles during endemic levels infest a large vigorous tree when several of these infested trees are in close proximity. Thus, the small numbers of beetles produced per tree are attracted to and infest the same large, vigorous tree in which beetle production will be high (Amman, 1978). A third theory is that warm dry weather, beneficial to the beetles but adverse to the trees, allows the beetle population to increase (Thomson *et al.*, in press; Safranyik *et al.*, 1975). Although we cannot predict when outbreaks will occur, considerable progress has been made in developing stand hazard rating methods and models to predict rate and amount of tree loss, should a stand become infested.

Identifying stands having characteristics conducive to beetle infestation permits managing those stands before outbreaks occur. Several methods for rating the hazard to pine stands are available. These are based on characteristics frequently associated with epidemics. Models are available to predict losses to mountain pine beetles based on stand structure and habitat type.

Characteristics in high-risk lodgepole pine stands are: average age more than 80; average diameter at breast height more than 20.3 cm (8 inches) in the United States (Amman *et al.*, 1977), but closer to 25.4 cm (10 inches) in Canada (Shrimpton and Thomson, 1983); and suitable climate for development based on elevation and latitude. Good results have been obtained by using age, diameter, and elevation to hazard-rate stands in Montana (McGregor *et al.*, 1981). Tree characteristics conducive to outbreaks in many stands occur when current and mean annual increment culminate (Safranyik *et al.*, 1974). Culmination of current and mean annual increment came closer to predicting time of outbreak than other tree and stand measures in Canada (Shrimpton and Thomson, 1983).

Other hazard-rating methods recognize the importance of these tree and stand characteristics for an outbreak to occur, but use differing measures of tree stress to indicate stand susceptibility. These are periodic growth ratio (Mahoney, 1978); crown competition factor and percentage of basal area that is lodgepole pine (Schenk *et al.*, 1980); and growth efficiency (Waring and Pitman, 1980). Although these methods have not been tested extensively, their applicability appears to differ considerably by geographic location (Amman, in press; Shrimpton and Thomson, 1983). Further tests of all hazard-rating methods to determine geographic area of applicability are planned as part of the Canada/United States Mountain Pine Beetle Program (Anonymous, 1983).

A rate of loss model has been developed to estimate the amount of tree and volume loss per year and the length of a mountain pine beetle infestation (Cole and McGregor, 1983). Model predictions consider differences in mortality by habitat types. Another modeling approach uses a mountain pine beetle model coupled to a growth prognosis model (Crookston *et al.*, 1978) and is expected to be published in the near future. This model allows growth of a stand and calling of a mountain pine beetle model to predict tree losses at any time during stand growth.

Knowledge of mountain pine beetle ecology has led to the development of two basically different strategies for reducing losses: preventive management and direct control. Preventive management is based on manipulation of tree and stand conditions to reduce vulnerability to beetle infestation, and is the most satisfactory long-term solution. In contrast, direct control involves killing or repelling beetles. Because direct control treats the symptom (too many beetles) of the problem, its effects are apt to be temporary. However, when properly used, direct control may reduce spread and intensification of infestations, as well as provide a holding action until susceptible stands can be treated silviculturally. Control options depend somewhat on size of the outbreak, age of the stand, size of the trees, and stand growing conditions. Options that will prevent rather than control beetle outbreaks should be emphasized. Large outbreaks usually cannot be stopped before tree losses render stands economically inoperable.

Silvicultural control measures are the most efficient means of preventing outbreaks. Patch cutting can be used to create a mosaic of age and size classes that reduces the acreage highly susceptible to mountain pine beetles at one time.

Thinning stands to 247 trees/ha (100 trees/acre) in northwestern Wyoming (Cole *et al.*, 1983) or to 18.4 m^2/ha (80 ft^2/acre) in western Montana (Unpublished data, Intermountain Forest and Range Experiment Station, Ogden, UT 84401), regardless of residual tree size, reduced tree losses to mountain pine beetle. On the Shoshone National Forest in northwestern Wyoming, 1 percent of the trees in the stands cut to 247 trees/ha (100 trees/acre) was killed, compared to 5 percent of the trees in the untreated check stands. On the Kootenai National Forest in western Montana, only 9 percent of the trees were killed in the 18.4 m^2/ha (80 ft^2/acre) basal area cut, compared to 91 percent loss of trees in the check stands. Beetle pressure was extremely heavy.

Other thinning treatments used in these areas also reduced tree losses to the beetles but were not as effective as the 247 trees/ha (100 trees/acre) and 18.4 m^2/ha (80 ft^2/acre) of residual basal area treatments in their respective areas.

Selective harvest of the larger trees in which beetle production is usually high will help to reduce losses where clear or patch cutting is not recommended (Cahill, 1978; Cole *et al.*, 1983; Hamel 1978). Such situations include riparian zones and areas of visual concerns, such as road rights-of-way, campgrounds, and scenic vistas.

Salvage logging is a commonly used direct control method. Salvage operations can retrieve wood that otherwise would be lost, and removal of beetle-infested trees causes reduction in the beetle population. The following principles (Safranyik, 1982) must be followed if direct control is to be effective: (1) Infestations must be detected early and direct control must be applied to the infested area within 1 to 2 years; (2) Treated areas must be inspected annually and retreated if necessary. Once a large outbreak has developed, however, salvage logging of infested material usually will not reduce future timber losses.

Combining salvage or logging with the use of semichemicals offers considerable promise (Borden *et al.*, 1983). Semiochemicals are used to attract beetles to trees that are going to be harvested. These infested trees then are removed from the forest and processed so that the beetle broods they contain do not mature.

Direct control requires the combined efforts of all landowners within the designated control area. Individual tree treatments can be used to suppress small spot infestations, alone or in combination with salvage operations. Treatments used to kill beetles under the bark are: (1) Heat – fell deck and burn trees; burn standing trees; fell and expose trees to solar radiation; (2) Pesticides – bark penetrating on felled trees. When beetle outbreaks are large, direct chemical control may not be cost effective, because treatment costs may exceed the value of wood in the beetle-infested trees and in trees apparently saved by the treatment. Insecticides provide a temporary control measure that slows infestations, but will not stop nor prevent outbreaks as long as stand conditions favoring the outbreak are not altered.

Individual, high-value trees can be protected by insecticides. Spraying selected trees before beetle attack does not require united effort by forest landowners as does direct chemical control. A single application prior to beetle flight offers protection for 1, and possibly 2 years (Smith *et al.*, 1977). Periodic treatments will be necessary for the duration of an outbreak.

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DAMAGE AND CONTROL OF THE MAJOR DISEASES OF LODGEPOLE PINE

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and
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ABSTRACT

The most important diseases of lodgepole pine in decreasing order of damage are dwarf mistletoe (*Arceuthobium americanum* Nutt), the stem rusts [*Cronartium* spp. and *Endocronartium harknessii* (J. P. Moore) Y. Hirat.], a group of root diseases, and finally, cankers and foliage diseases. Dwarf mistletoe, a vascular parasitic plant, causes increment losses which become more severe with time since infection and finally results in decline and death of the host. Control requires even-aged management with eradication of the parasite at harvest plus provisions to prevent or retard reinvasion from stand edges.

Severe damage by the pine stem rusts is limited to a relatively narrow range of ecological conditions. For some species and regions these have been identified. Management involves an adjustment of stocking to provide for increased mortality, using as a guide locally measured rates of mortality. Resistance is at least in part controlled genetically, and tree improvement programs should take rust resistance into account.

Root diseases are locally damaging. Most can survive on dead root systems, so that the infected area becomes nonproductive. Management requires the use of resistant species or destruction of the inoculum by stump and root extraction or fumigation. Cankers and foliage diseases can cause local damage. Direct control measures are either not available or not recommended. Damage in most cases is limited to temporary increment loss or, in the case of cankers, deformation of the bole and breakage.

INTRODUCTION

Lodgepole pine (*Pinus contorta* Dougl.) is subject to a number of damaging diseases (Baranyay, 1975; Krebill, 1975). Any comprehensive discussion of the productivity of this species must consider their effect. Fortunately, there has been considerable progress over the last few decades in our understanding of these diseases. For many, we can begin to predict where and when they will occur, and what their effect on stand development and productivity might be. Furthermore, it is now possible to recommend silvicultural practices which will reduce the losses. On the other hand, a great deal remains uncertain and continued research and careful monitoring of control programs will undoubtedly lead to further improvements.

In this paper we discuss the major diseases of lodgepole pine, paying special attention to their effect on productivity, and the disease management strategies which might reduce these effects. For a species that occurs over so large a geographic and ecological range, it is not surprising that there should be a good deal of local variation. It should, therefore, be understood that specific disease management prescriptions will vary from place to place.

The most important pathogen of lodgepole pine throughout its range is dwarf mistletoe (*Arceuthobium americanum* Nutt ex. Engelm.). Next in importance rank the stem rusts, followed closely by the root diseases. Finally, there are a number of pathogens of bark and foliage.

DWARF MISTLETOE

Dwarf mistletoes are the most significant damaging agents in lodgepole pine essentially throughout the range of the tree. Although eight species are found on this tree, only the lodgepole pine dwarf mistletoe, *Arceuthobium americanum*, is of economic importance. This dwarf mistletoe occurs from northern British Columbia and Alberta (to about 59° north latitude), south to central California and central Colorado (Hawksworth and Wiens, 1972). *A. americanum* occurs on *Pinus contorta* vars. *latifolia* and *murrayana* essentially throughout their ranges. *A. americanum* also attacks the *P. contorta* x *P. banksiana* hybrid in northern Alberta, and jack pine from Alberta to Ontario.

Recent estimates of dwarf mistletoe incidence in lodgepole pine show that nearly 40 percent of the type in the Rocky Mountains of the U.S.A. is infected (Table 1). In California, Oregon, and Washington, 42 percent of the lodgepole pine type is affected (Bolsinger, 1978). In the central Rockies (southern Idaho, Wyoming, Utah, and Colorado), infection averages about 50 percent. In several National Forests infection runs over 60 percent: Medicine Bow, Shoshone and Bridger-Teton in

Table 1. – Recent estimates of dwarf mistletoe incidence and losses in lodgepole pine in the Rocky Mountain States, U.S.A. (Drummond, 1982).

Region (States)	Commercial lodgepole pine Area		Percent infected	Estimated annual loss due to dwarf mistletoe	
	M ha	(M acres)		m^3(1000)	(MCF)
Northern (Montana, N. Idaho)	2,400	(5,931)	29	516	(18,210)
Rocky Mountain (Colorado, Wyoming)	730	(1,799)	51	270	(9,550)
Intermountain (W. Wyoming, Utah, Idaho)	980	(2,420)	59	495	(17,490)
TOTALS	4,110	(10,150)	39	1,281	(45,250)

Wyoming; and Caribou, Sawtooth, and Targhee in Idaho (Dooling and Eder, 1981; Johnson *et al.*, 1981; Hoffman and Hobbs, 1979).

Estimates of combined annual losses because of reduced growth rates and increased mortality in lodgepole pine are estimated at 1.28 million m^3 (45.2 million ft^3) in the Rocky Mountains of the U.S.A. (Table 1), and 2.5 million m^3 (90.2 million ft^3) in British Columbia (Van Sickle and Smith, 1978). No estimates of mistletoe-caused losses in lodgepole pine in Oregon, Washington, or California are available, but more than 1 million acres are infested in those states (Bolsinger, 1978).

In addition to growth loss and increased mortality, dwarf mistletoes affect their hosts in other ways: they reduce cone and seed crops (Schaffer *et al.*, 1983), reduce wood growth (Piirto *et al.*, 1974; Dobie and Britneff, 1975), and predispose trees to attack by secondary pests, particularly bark beetles.

Dwarf mistletoes are one of the few diseases for which silvicultural controls are effective (Scharpf and Parmeter, 1978). Once dwarf mistletoes are drastically reduced in a stand, they re-develop slowly because of their slow rates of spread (less than 0.5 m per year) and long life cycles (6+ years).

The most effective control, of course, is to minimize infection in young stands. In many mature infected lodgepole pine stands, this is most easily accomplished by clearcutting. A main factor for consideration in mistletoe infested stands is to lay out the clearcut units with mistletoe in mind. For example, to minimize subsequent reinvasion of dwarf mistletoe, the edges of the clearcut, insofar as possible, should be in healthy stands or non-lodgepole pine. To minimize reinvasions if infected edges have to be left, clearcut patches should be at least 8 to 16 ha. (20 to 40 acres). Below this size, the ratio of perimeter to area increases very rapidly (Fig. 1).

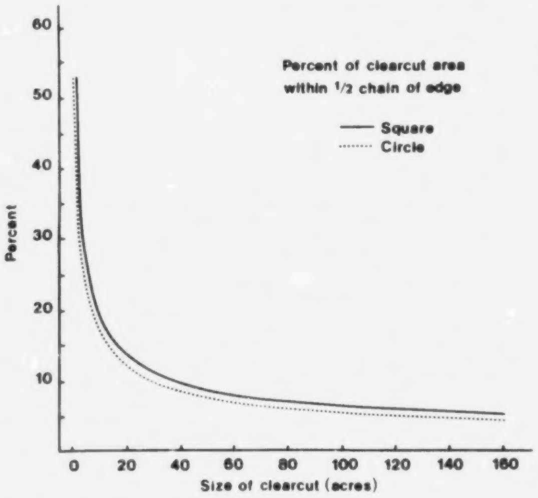

Figure 1. – Relationship between clearcut area and proportion of the clearcut within ½ chain (10 m) of the edge, the effective maximum distance of dwarf mistletoe spread.

The aim should be to eliminate mistletoe from the area by clearcutting and subsequent removal of all infected residuals. Since mistletoe symptoms on advanced regeneration may not be obvious, all advanced regeneration should be removed. This might be achieved by broadcast burning, provided there is a good distribution of fuel (Alexander and Hawksworth, 1975). Alternatively, advanced regeneration may be killed by hand clipping or by machines such as the Marden chopper or possibly herbicides.

Failure to treat clearcut areas in this fashion will lead to perpetuation of mistletoe losses. In recently logged and regenerated areas that have not been appropriately treated, removal of taller infected residuals is recommended. Each of these will otherwise become the centre of an area of severe infection. Infection on young regeneration (under 10 years old) is uncommon. Such trees represent a very small target area for mistletoe seed and often escape infection.

Recent experience in mistletoe infested stands indicates that thinnings or partial cuttings are feasible, providing that the level of infestation is not too high (Alexander and Edminster, 1980; Dooling and Brown, 1976). The RMYLD program (Edminster, 1978; Cole and Edminster, these proceedings) enables forest managers to predict yields in individual healthy or mistletoe infested stands subject to various management alternatives (thinning intensity, thinning intervals, rotation ages).

A comparison of estimated yields in lodgepole pine of three growing stock levels (GSL,) 13.8, 23.0, and 32.1 m^2 ha^{-1} (60, 100, and 140 ft^2 ac^{-1}), and various intensities of infection are given in Table 2. Intensity of infection is based on the 6-class (DMR) rating system (Hawksworth, 1977). For the comparisons, these conditions are assumed: present age, 60 years; 1483 trees per ha (600 trees per acre); site index, 18.3 m (60 feet); average d.b.h., 15.2 cm (6.0 in); thinning interval, 20 years. Projections are made for a 60-year period to rotation age 120. The results show that, for healthy and lightly infected stands (up to DMR 2), anticipated yields increase with growing stock levels. For stands with an infection rate of DMR 3 or 4 at the beginning of the period, there is little relationship between GSL and yields, and for heavily infested (class 5) stands, yields decrease with increasing GSL. For example, in DMR class 5 stands with a GSL of 13.8, anticipated yields are 36 percent of comparable healthy stands, but are only 14 percent for DMR class 5 stands with a GSL of 32.1 m^{2}ha^{-1}. The same trend in mean annual increment is shown in Figure 2.

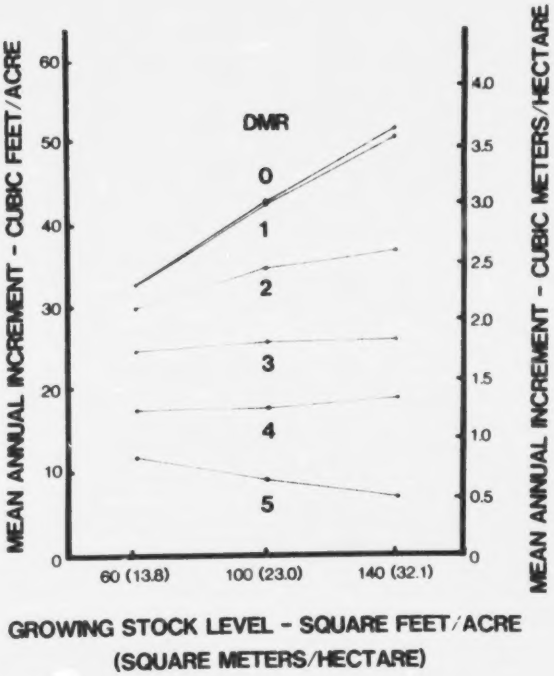

Figure 2.–Relationship of mean annual increment at rotation age (120 years) and growing stock level for six mistletoe intensity classes at age 60. Site index 18.3 m (60 feet), thinning interval 20 years.

The predicted merchantable cubic foot and metric volume from age 60 to 120 in stands of various mistletoe intensities is given in Figure 3. Very light infections (class 1) have no significant effect on yields, but all other infection classes do. Even stands with an intensity of 2 at age 60 will have high infection levels (DMR 5+) by age 120.

The influence of dwarf mistletoe infection on average stand diameters is shown in Figure 4. Again, infection class DMR

Table 2.–Total yields at age 120 in merchantable cubic feet per acre in Rocky Mountain lodgepole pine. Stands now 60 years old. Site index 60, thinning interval 20 years.

Dwarf mistletoe rating at age 60	Growing stock level 60		100		140	
	Yields	% Healthy stand	Yields	% Healthy stand	Yields	% Healthy stand
0	3970	100	5180	100	6270	100
1	3930	99	5120	99	6170	98
2	3640	92	4200	81	4390	70
3	2980	75	3160	61	3130	50
4	2170	55	2220	43	2240	36
5	1420	36	1110	21	860	14

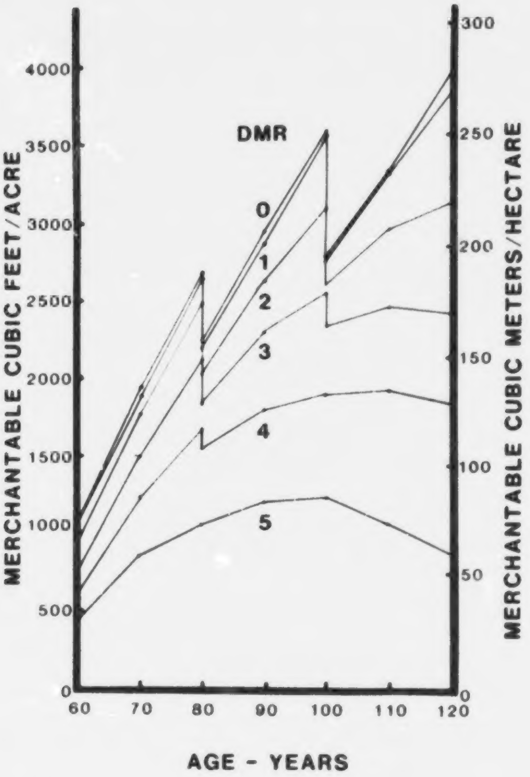

Figure 3. – Projected yields (merchantable cubic feet/acre and meters/hectare) in stands of various infection intensities at age 60. Site index 18.3 m (60 feet), thinning interval 20 years, growing stock level 23.0 m^2ha^{-1} (100 ft^2ac^{-1}).

Table 3. – Maximum stand dwarf mistletoe ratings for estimated losses (percent of yields in mistletoe-free stand). Site index 60, thinning interval 20 years).

Growing stock level	Percent volume reduction					
	10	20	30	40	50	60
60	2.1	2.7	3.2	3.7	4.3	4.7
100	1.5	2.0	2.5	3.1	3.6	4.1
140	1.3	1.6	2.0	2.5	3.0	3.7

1 has no measurable effect, but higher ratings have progressively more effect, so that by class DMR 5, no measurable growth increase over the last 20 years is apparent.

The effects of dwarf mistletoes on a stand depend on a combination of the intensity of infection, and stand density. For a given intensity of infection, effects are most pronounced in dense stands. Table 3 shows the estimated percent volume loss to mistletoe in relation to infection intensity and growing stock level. For example, for stands rated as 2 at age 60, estimated volume reduction is 10, 20, and 30 percent for stands of GSL 13.8, 23.0, and 32.1 m^2 ha^{-1}, repectively. Another way to use this table is to decide what level of loss is acceptable, and then adopt management treatments to keep the infection below a given stand rating. For example, if a 30 percent loss can be tolerated, stand mistletoe ratings should be kept below 3.2 for GSL 13.8 (60 ft^2 ac^{-1}); 2.5 for GSL 23.0 (100 ft^2 ac^{-1}); and 2.0 for GLS 32.1 (140 ft^2 ac^{-1}).

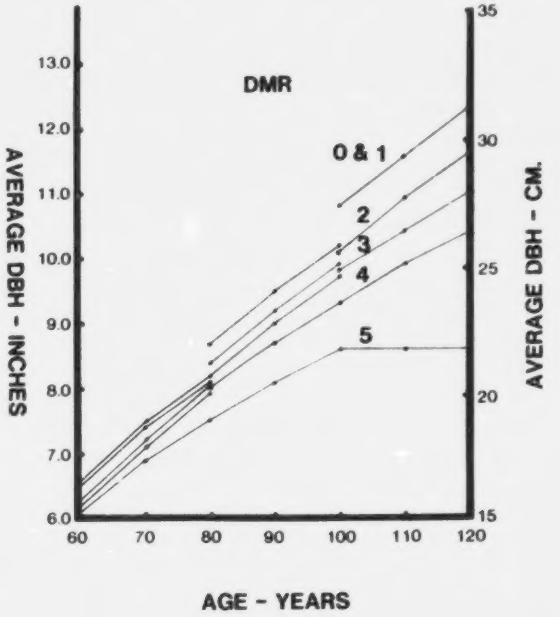

Figure 4. – Relationship between diameter growth and dwarf mistletoe intensity (DMR). Mistletoe ratings at age 60. Site index 18.3 m (60 feet), thinning interval 20 years, growing stock level 23.0 m^2ha^{-1} (100 ft^2ac^{-1}).

RUSTS

Lodgepole pine is subject to several rusts. Those affecting foliage do relatively little damage except for occasional outbreaks on seedlings. Those attacking stems are dangerous. The pine stem rusts belong to the genus *Cronartium*. Most have a complete rust life cycle. The most common species are *C. coleosporioides* Arth. (= *C. stalactiforme* Arth.), *C. comandrae* Peck, *C. comptoniae* Arth. Aeciospores are produced by perennial infections on pine in spring, and infect the alternate host. The rust builds up on this alternate host all summer and reinfects pine in late summer and fall. Western gall rust, caused by *Endocronartium harknessii* is an exception. Here spores produced on pine in spring reinfect pine directly. In Canada the stem rust life cycles and alternate hosts have all been determined. In the central Rocky Mountain areas of the U.S.A., the situation is much more complex and some doubt remains about the exact taxonomic status and life cycles of some of the less common members of this group. However, the important ones are known.

The stem rust mycelium develops in the bark of branches and stems, eventually killing affected tissues. For most species this mycelium grows along the bark from the point of invasion. Many potentially lethal stem infections arise on branches. Western gall rust is an exception. This rust induces a woody gall at the point of infection, and the mycelium remains restricted to this gall. Death is often hastened by rodent gnawing and attack by other secondary agents. Small branches are killed quickly, but it may take decades to girdle and kill stems. As a result, infected trees continue to occupy growing space for a long period.

In central British Columbia western gall rust and stalactiform rust are the most common species, while comandra blister rust is often the most damaging stem rust of lodgepole pine in the Rocky Mountains of the U.S.A. In some areas, the amount of damage equals or exceeds that caused by dwarf mistletoe. Damage to lodgepole pine by comandra blister rust is most severe in western Wyoming. For example, the lodgepole pine type on the Wind River District of the Shoshone National Forest amounts to about 20,000 ha. It was found that 50 percent of the lodgepole pines over 12 cm d.b.h. were infected (Geils and Jacobi, in press). In some stands, more than 70 percent of the trees are infected and up to 30 percent of the trees are dead because of comandra rust (Brown, 1977). Geils and Jacobi (in press) estimated that there were 600,000 dead, standing lodgepole pine (over 12 cm d.b.h.) on the district, two-thirds of which were killed by comandra blister rust.

All stands are not equally infected. Rather, each rust species requires a particular set of environmental conditions which allow pine and the alternate host to grow together, and which provide suitable conditions for infection. Severe damage by these rusts is typically limited to certain restricted ecological conditions in which these requirements are met. For some species, these conditions have been identified (Beard *et al.*, 1983). It is not surprising that western gall rust, which does not require an alternate host, is much more common and widespread than any of the other stem rusts.

Even in heavily infected stands one usually finds many uninfected trees. This appears to arise from a considerable degree of variation in resistance among trees. There is good evidence that this resistance is genetically controlled. In dense, natural stands, these rusts behave as slow-acting natural thinning agents. In managed stands, however, where stocking levels are deliberately kept low from an early age onward, additional mortality due to stem rusts can become damaging. In addition, the more open managed stands may also harbour larger populations of the alternate host, thereby increasing the risk of infection. In known high-risk areas, allowance should be made for rust mortality by keeping initial stocking levels somewhat higher than would otherwise be desirable.

Thinning or spacing operations should remove diseased trees. In more heavily infected stands this may prove difficult because western gall rust, and perhaps the other rusts as well, are commonly found on the larger trees.

There is potential for increasing resistance to cronartium rusts by selection and breeding. However, current tree improvement programs usually do not include a rigorous disease resistance test and, because such programs will tend to reduce genetic variability, they may lead to higher disease losses. Also, pine growing in areas where the ecological conditions are not suitable for a particular rust, fails to develop (or loses) resistance. If such provenances are moved to high-risk areas, they will show much higher infection levels than the local pine population. Tree improvement programs which draw selections from large areas including low-risk stands, may be frustrated by the same phenomenon.

In summary, major damage by the stem rusts of pine is restricted to certain ecologically definable areas. In such areas the risk of mortality can be estimated, and stocking guides should be designed to allow for this additional mortality. Pine selection and breeding programs for stock to be used in high risk areas should take rust resistance into account.

ROOT DISEASES

The more common root diseases of lodgepole pine include *Armillaria mellea, Polyporous circinatus, P. schweinitzii* and *Verticicladiella wagenerii.* The first three of these commonly cause root and butt rot, windthrow, and some mortality, in localized stands scattered throughout the range of lodgepole pine. They can be expected to survive in root systems and stumps from one rotation to the next. Infection centres will spread slowly, and infected areas are essentially nonproductive. Experience with other species suggests that such infection centres might be eradicated by mechanical removal of stumps and major roots or by injection into the soil of volatile fungicides. A switch to nonhost species will also effectively circumvent the problem.

Verticicladiella wagenerii is a pathogen affecting the vascular system. The fungus is apparently introduced into stands by insect vectors. Once established, the disease can spread to surrounding trees via root grafts and contacts. Mortality usually follows quickly. This pathogen cannot survive long in dead trees or stumps, and, hence, it does not reinfect regeneration following logging. On the other hand, infected stands may represent a source of insect vectors carrying the disease, which threatens surrounding healthy stands.

Fomes annosus presents an enigma. The pathogen is uncommon in lodgepole pine. It has not been recorded in British Columbia pine stands and is rare in Oregon (Thies, 1979). In fact, Pacific Northwest pine stands constitute probably the only large natural pine area in the world free of serious *F. annosus* problems. This is the more surprising if one considers that *F. annosus* is common in the wet coastal and mountain forests on hemlock, spruce, and true firs, and that lodgepole pine has been shown to be very susceptible in Europe (Redfern, 1982; Wagn, 1978). Recent work in Finland has demonstrated that European *F. annosus* consists of at least two distinct forms which behave very differently and are largely sexually incompatible (Korhonen, 1978). The "S" race develops primarily on spruce and true fir, causing butt rot, windthrow and increment loss but little direct mortality of standing trees in older stands. The "P" race occurs mainly on pine where it causes typical root rot centres with considerable mortality. Preliminary evidence suggests that this division of races holds true for North America as well. It would seem that *F. annosus*, in the Pacific Northwest forests at least, behaves like the "S" race, typically causing butt rot in hemlock, spruce, true firs, and Douglas-fir. The "P" race may be absent. If so, the European pine race, which is also present in eastern North America, is a potentially dangerous pathogen of lodgepole pine. On the other hand, it may also be that our conditions, particularly our acid soils, are not suitable for the "P" form of *F. annosus*.

CANKERS

Lodgepole pine is subject to a number of bark diseases. Some typically affect young shoots and branches; others attack the bark of the main bole. The most important is the bole canker caused by *Atropellis piniphilla*. This disease is most prevalent in the northern Rockies, particularly in Alberta. The pathogen attacks boles at nodes, either within or just below the live crown. Infection before age 25 is uncommon. Each infection develops into a long, narrow, resinous lesion that can be mistaken for *Cronartium coleosporioides*, but may be identified by the dark, blue-gray stain in the xylem underlying the lesion. Infection levels vary. Some stands remain essentially free of the pathogen, but infection levels as high as an average of three stem cankers per tree are not uncommon. In Alberta, areas with high summer rainfall tend to have higher infection levels. Mortality is uncommon. Damage results from stain, malformation of the bole, and occasionally breakage. We have no control methods. However, because of the very slow lateral growth of the fungus, fast growing trees are not as greatly affected. Occasionally, lesions may be overgrown.

FOLIAGE DISEASES

Lodgepole pine is attacked by a large number of foliage diseases (Hunt, 1981; Krebill, 1975). Most have a regular annual life cycle with a short period of spore release and infection during the growing season. Some can reproduce more quickly, utilizing any period of suitable infection conditions, usually wet weather above a minimum temperature.

Foliage diseases can be spectacular. During epidemics all the one-year-old and older foliage may be attacked and lost. However, such epidemics do not, as a rule, last long, and damage is restricted to some increment loss. In seedlings, mortality may result, and these diseases can be troublesome in nurseries.

There are a number of natural control mechanisms which limit damage. Firstly, in many areas, the requisite conditions for heavy infection do not occur very often. Secondly, most foliage diseases of pine are limited by specific secondary fungal parasites which invade infected foliage only and prevent spore production by the primary parasites. Finally, there is at least some genetically controlled variation in resistance between trees for most of these diseases. Uniform heavy infection of all trees in a stand is uncommon.

In summary, losses due to foliage diseases are restricted to increment loss during years of heavy infection. The overall losses are probably small compared to those caused by other pathogens, and specific control measures are not warranted, except in nurseries.

SUMMARY

In summary, lodgepole pine is attacked by a number of diseases which may cause substantial reduction in productivity of trees and stands. The most important of these, in decreasing order of damage, are dwarf mistletoe, stem rusts, and root disease. The effect of dwarf mistletoe in existing infected immature stands can in many cases be predicted. Successful management requires that the major disease problems and risks be identified at the stand level, and that subsequent silvicultural prescriptions be amended to reduce or avoid losses.

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ROLE OF FIRE IN LODGEPOLE PINE FORESTS

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ABSTRACT

Fire is one of the most important factors involved in the establishment and development of many lodgepole pine forests in North America. In the Rocky Mountains lodgepole pine is usually considered a fire-maintained seral type. But even here fires vary greatly in frequency, intensity, size, and other characteristics. A particular fire regime greatly affects forest succession, longevity of the species, stocking, and species composition; and fire also influences the incidence of insects and diseases. Fuel quantity changes over time and with it fire behavior potentials in natural and slash fuels. Fire behavior potentials are greatest when buildup of dead fuel coincides with development of understory conifers. Most fires are low intensity, creeping, surface fires, but high intensity crown fires during severe weather burn the most acreage. Fires, stand development, mortality influences, and fuel accumulation interact in a complex network. Sound management of lodgepole pine requires that we understand the complexities of lodgepole pine ecology, including the role of fire, and manage fire within that context.

INTRODUCTION

Most lodgepole pine (*Pinus contorta*) forests were established as a result of fire, particularly in the Rocky Mountains. The role of fire in lodgepole pine ecosystems was recognized by ecologists in the early 1900s (e.g. Clements, 1910; Mason, 1915). Lodgepole pine is abundant in much of western North America and is largely a result of repeated fires (Smithers, 1961; Wellner, 1970; Habeck, 1976; Brown, 1975; Lotan, 1975a, 1976; Perry and Lotan, 1979). Successional trends are frequently interrupted by fire and original stands are replaced with essentially pure stands of lodgepole pine. Fire frequency seems to also affect cone serotiny in lodgepole pine stands (Lotan, 1976; Perry and Lotan, 1979; Muir and Lotan, In press). The effects of fire, fuel accumulation, stand development, and incidence of insects and disease in lodgepole pine forests are all part of complex biological and physical relationships in what is oftentimes considered to be a simple ecosystem. The species has an amazing tenacity to survive a wide variety of environmental situations and to endure under differing fire regimes.

Brown's (1975) excellent review of the role of fire in lodgepole pine at the previous lodgepole pine symposium held in Pullman, Wash. in 1973, is a frequently cited reference. The current paper highlights pertinent relationships between fire and the species, for the most part in the Northern Rocky Mountains, and updates Brown's information. Fire regimes, fire behavior, fuel dynamics, community dynamics, succession, cone serotiny, stand establishment and development, and insect and disease relationships are discussed.

THE NATURE OF FIRE IN LODGEPOLE PINE FORESTS

That lodgepole pine forests occur over a wide variety of environments is a well established fact (Pfister and Daubenmire, 1975; Lotan and Perry, 1983). It follows then that the fire regimes affecting lodgepole pine forests also vary considerably (Brown, 1975; Arno, 1980; Kilgore, 1981; Martin, 1982). Fire regimes are the particular pattern of fire frequency and intensity occurring within a particular ecosystem (Kilgore, 1981). These fire regimes depend not only upon the vegetation and topography involved but also upon the climatic regimes that determine the coincidence of ignitions and the burning conditions.

Brown (1975) illustrated many interrelated factors that influence the fire regime in lodgepole pine forests (fig. 1). He pointed out that seedling establishment and subsequent development of stand density, age structure, and composition depend in part upon the type of fire that last occurred. In turn, characteristics of the developing stand influence the type of fire that will next occur and when it will occur (fire regime).

Fire Regimes

Fire Frequency

Arno (1980) concluded that fire has historically been more frequent in lodgepole pine than previously realized. He reported fire-free intervals of only 22 to 50 years in many lodgepole pine-dominated stands in the northern Rocky Mountains (table 1), yet some high elevation areas have fire-free intervals measured in centuries (Romme, 1980).

Fire-scarred lodgepole pine resulting from low-intensity surface fires are fairly common. Prior to the advent of fire suppression low-intensity surface fires were common in the Bitterroot National Forest in Montana (Arno, 1976), in Jackson Hole in Wyoming (Loope & Gruell, 1973), and in the Bob Marshall Wilderness in Montana (Gabriel, 1976). Although we know that most individual fires were low-intensity, creeping, surface fires, today most acreage burned is by the high intensity crown fires that occur during severe weather: dry and/or windy conditions. A particular fire regime in lodgepole pine forests greatly affects seedling establishment, stand density, age structure, and species composition.

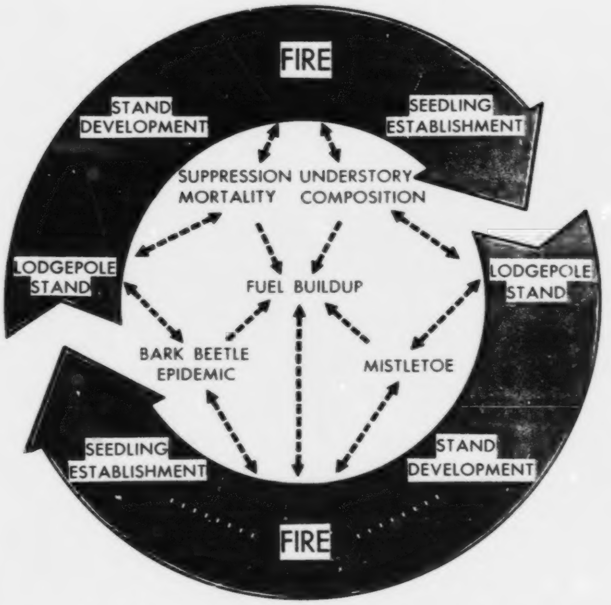

Figure 1. – Lodgepole pine fire cycle showing the complexities of the many interrelationships involved.

Table 1. – Fire-free intervals in lodgepole pine stands.

Fire-free intervals (years)	Location	Investigator and dates
22	Bitterroot Valley, Mont.	Arno, 1976
27	Jasper National Park, Alberta	Tande, 1979
40	Bitterroot Valley, Mont.	Arno, 1976
40	Bob Marshall Wilderness, Mont.	Gabriel, 1976
50	Jackson Hole, Wyo.	Loope & Gruell, 1973
67	Rocky Mountain Foothills, Alberta	Day, 1972
300	Yellowstone National Park, Wyo.	Romme, 1980

Frequent low intensity fires may thin lodgepole pine stands without doing serious damage. They may also induce decay or beetle activity. As stands become older they become more flammable due to events that occur throughout the life of the stand. This may be due to fires, to overmaturity, insects and disease outbreaks, or other events. Eventually fuel conditions become hazardous, weather becomes extremely dry, lightning or other incidents ignite fuels, and the stand burns, usually at the expense of associated tree species.

In some years the area burned is extensive. Barrows (1951) estimated that some 12 million acres (4.8 million ha) burned in the northern Rocky Mountains between 1908 and 1947. During the infamous 1910 fire season alone nearly 4 million acres (1.6 million ha) burned, much of it in lodgepole pine forests. Fire has no doubt burned all forest ecosystems at least once on the order of every few centuries. Fire is part of the history of Rocky Mountain lodgepole pine. The major ecological effect is the disruption of forest succession, and lodgepole pine usually capitalizes on this disruption.

Fire Behavior

In many lodgepole pine stands, fire is an "all or nothing" proposition: either smoldering and creeping over the ground or developing into rapidly moving, intense crown fires. Further, large, summer wildfires typically display both low- and high-intensity fire behavior triggered by diurnal weather changes as described in detail by Muraro (1971).

Most fires in lodgepole pine forests are of low intensity because surface fuel properties are not conducive to high flammability. Fires may go out in a day or two after they start or they may smolder in duff and rotten wood for weeks and even months without making sustained runs, as observed in Yellowstone National Park (Sellers and Despain, 1976). Fires are more flammable, however, in parts of Canada where *Cladonia* lichen is an abundant surface fuel on dry sites (Lawson, 1972). Fires here are more apt to spread as a flaming front but usually at low intensity. Lawson (1973) measured an average fireline intensity of 35 Btu/s/ft (range was 7 to 125 Btu/s/ft) for 28 test fires in fuels containing *Cladonia*, dwarf huckleberry (*Vaccinium spp.*), needle litter, and limited amounts of downed woody fuel. Spread rates averaged 2.6 ft/min (range was 0.9 to 6.5 ft/min). It required up to 48 minutes after ignition for fires to reach a steady state rate-of-spread. Mid-flame wind speeds ranged from 0.8 to 3.3 mi/h. Mathematical model predictions (Rothermel, 1972; Albini, 1976) for the Selway-Bitterroot fuel data (table 2) produced rates of spread and fireline intensities similar to those reported by Lawson. Fires in these fuels are marginally sustainable and easy to control by direct attack using hand tools.

The Shoshone National Forest data (table 2) exemplifies the high end of the flammability scale in lodgepole pine surface fuels. Predicted fireline intensities were several times greater (200 to 400 Btu/s/ft) than the other locations due to heavier loadings of litter and downed woody fuels. At low moisture contents these fuels have high potentials for crowning and spotting and indirect attack would probably be necessary to suppress fire.

High intensity fires are most probable where dead fuels have accumulated (fig. 2). Concentrations of dead fuels or mixed dead and live fuels cause torching of individual trees and groups of trees. High winds and steep slopes can then produce running crown fires. These may occur as narrow stringers of crown fire up the sides of steep mountains or involve much larger areas.

Table 2. – Average loadings of the forest floor litter layer, downed woody material less than 3 inches diameter and understory herbaceous vegetation and shrubs from large numbers of samples at different locations.

Location	Plots	Litter	Less than 3" woody material	Herbs & shrubs
	Number	tons/acre		
Selway-Bitterroot Wilderness, Idaho	360	0.6	1.4	0.94
Shoshone National Forest, Wyo.	190	1.1	4.0	0.28
Bitterroot National Forest, Mont.	400	0.3	3.4	0.92
Central British Columbia (Lawson, 1973)	–	0.2	0.5	0.17
Front Range, Colo. (Alexander, 1979)	365	1.4	2.7	0.13

The frequency of high-intensity crown fires varies by locality. Reported frequencies of stand replacement fire range from 67 years in Alberta (Day, 1972) to in excess of 300 years in Yellowstone National Park (Romme, 1980).

The open, self-pruning crowns of lodgepole pine are less prone to crowning than species such as spruce and subalpine fir (*Abies lasiocarpa*) that have dense crowns often containing dead branchwood (Despain and Sellers, 1977). Fahnestock's (1970) rating of crown fire potential places lodgepole pine as low as any conifer and with two to three times less crowning potential than closed-crown species. The likelihood of crowning fire in lodgepole pine depends on the heat from surface fuel and particularly the distance above ground to the crowns. Potential fire intensity and fire size depend, in part, on the spacing of trees and quantity of crowns per unit area. Thus, fire behavior potential of crown fuels depends upon stand conditions which, in turn, are frequently affected by the nature of the preceding fire. In this way, fire and stand development are mutually related (Brown, 1975).

In resistance to fire, lodgepole pine has traditionally been rated between the most fire-resistant western larch, ponderosa pine, and Douglas-fir and the least fire-resistant subalpine fir, western hemlock, and Engelmann spruce (Wellner, 1970 after Flint, 1930).

Rates of spread and fire intensities are not as great in forests composed of larch, Douglas-fir, western white pine, and cedar/

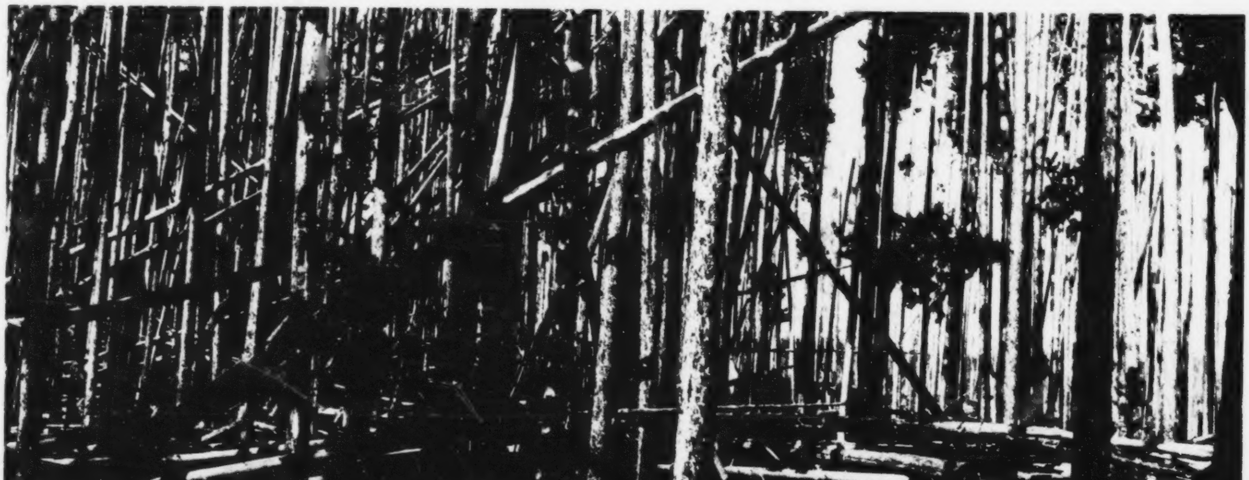

Figure 2. – Fuels as the result of mountain pine beetle infestations 30 years before photo was taken, Bitterroot National Forest, Mont.

hemlock (Lyman, 1945), but are greater than in spruce, fir, and aspen. The duff of lodgepole pine dries rather rapidly (Smithers, 1961).

Brown (1975) reported comparative fire data from Barrows (1951):

> *Ignition Potential.* – The number of fires per million acres:

–Species–	–Number–
Fir/larch	40
Lodgepole pine	50
Douglas-fir	70
Grand fir	410

> *Rate of Spread.* – Averaged 132 ft (40m) of perimeter per hour from origin of fire to time of attack by suppression forces. This is the average for all forest types. It is greater than spruce/fir and less than for Douglas-fir and ponderosa pine.

> *Fire Size.* – Only ponderosa pine exceeded lodgepole pine in percentage of fires greater than 10 acres (4 ha).

	–Percent–
Less than ¼ acre	76
Less than 10 acres	95
Less than 300 acres	99

> *Ignition Potential by Fuel Type.* – Percentage by material first ignited.

	–Percent–
Duff	36
Green treetops	5
Snags	30
Grass	10
Wood on ground	14
Miscellaneous	5

Although lodgepole pine is intermediate in fire potential when compared to other species, under certain conditions stand-replacing fires burn vast areas. Apparently, the long fire cycles lead to extremes in fire behavior.

FIRE-STAND-FUEL INTERACTIONS

Stand structure, fuel succession, and fire, are interrelated. They all depend upon the nature of mortality that occurs during stand development (fig. 1). For example, an insect epidemic that causes considerable tree mortality also leads to an accumulation of downed dead fuel (fig. 2). In turn, the accumulation of fuel increases the chances of a high-intensity, stand-replacing fire. A high intensity fire has a different influence on regeneration than a low intensity fire. Finally, the composition and structure of a new stand influences its susceptibility to mortality.

Mortality and Fuel Buildup

In response to natural mortality and factors causing downfall, dead fuels accumulate on the ground. Causes of mortality such as fire, insects and disease, competition or natural thinning, and wind damage impact stands at erratic intervals. Thus quantities of downed woody fuel accumulate in an irregular manner not necessarily related to stand chronology. Because of irregular accumulation, prediction of downed woody fuel loadings in specific stands from characteristics of the stand has not proved reliable (Brown and See, 1981; Alexander, 1979; and Muraro, 1971). Quantities of lodgepole pine crowns that are potentially slash fuels following harvest, on the other hand, can be reliably predicted (Brown, 1978; Gary, 1976; Kiil, 1967).

Stand development, vegetation mortality and fuel buildup, and fire interact dynamically in lodgepole pine forests (Brown, 1975). Historically, fire may have created more surface fuels than any other single cause of mortality. Subsequent fuel buildups vary depending upon fire intensity. In high-intensity fires, an entire stand is killed and eventually falls to the ground, creating a large fuel buildup. Low-intensity fires kill fewer trees and create less fuel. The thinning effect on the stand, however, opens it up to increased wind and sunlight, which increases flammability. Low-intensity fires may also decrease fuel loadings.

Suppression mortality begins soon after dense stands are established and can contribute significantly to surface fuels. Where crown competition is not severe, suppression mortality creates little fuel. The intensity of the preceding fire, which influences seedbed condition and seed supply, affects density of the new stand; thus, determines whether suppression mortality is a factor in fuel buildup.

Insects, particularly the mountain pine beetle *Dendroctonus ponderosae* Hopk., create ground fuels by killing trees and opening up stands for drying. Today, this cause of mortality probably overshadows all others as a cause of fuel buildup.

Diseases such as root rots and canker rots can cause ground fuel buildups of local importance; however, they are of less importance than other sources of mortality. Low-intensity fires can encourage rot infections by forming basal fire scars that serve as entry points for pathogens (Nordin, 1958). Fire-scarred trees subsequently infected by fungus also appear to be selectively killed by beetles (Geiszler, 1980). Recent investigations indicate that root damage from burnout of large woody fuel may be the most important source for stem decay (Gara and others, this proceedings). This suggests an interesting link between fire, disease, and fuel buildup. Another pathogen, dwarf mistletoe, *Arceuthobium americanum*, can add significantly to surface fuels particularly in older stands.

The presence of dwarf mistletoe and mountain pine beetle in lodgepole pine stands increase flammability of the stand. The mountain pine beetle by attacking and killing mature to overmature trees increases the heavy fuel loads in the stand at a time when the stand itself is approaching a high fire hazard.

Dwarf mistletoe by decreasing the tree growth has been suspected of predisposing the tree to mountain pine beetle and accelerating fuel build-up, but evidence has not been substantiated. In the absence of mountain pine beetle, dwarf mistletoe increases fire hazard by stimulating epicormic branching of the tree, thereby enhancing vertical continuity.

Though lodgepole pine, mountain pine beetle, and dwarf mistletoe all influence characteristics of fire, fire itself often enhances potential fire behavior of future fires. The intensity of fire will have a role in determining stand density and future fuels potential. For instance, a high-intensity fire will usually be followed by a dense stand due to opening of serotinous cones and exposed mineral soil.

Breakage from wind and snow and other specific causes of mortality contribute to buildup of downed woody surface fuels. Thus we have interrelationships among many variables, with some processes governed by laws of chance. This means management actions can have far reaching effects on fuels and stand development, and that prediction of surface fuels requires more than just knowledge of stand characteristics. Stand history is extremely important.

Fuel Accumulation and Fuel Succession

Fuel accumulation refers to an increase in fuel quantities over time. Fuel succession is the change in fuel characteristics over time and involves both increases and decreases in fuel quantities and is the term preferred by the authors because it more nearly describes what takes place over time. Vegetative biomass increases regularly over time; however, all biomass is not fuel. Decay of fuel can be greater than accretion, resulting in a net decrease in fuel. Thus, the term fuel succession more correctly describes the dynamics of fuel with time (Brown, In Press). In lodgepole pine forests as perhaps in all forests, live and dead fuels as well as small and large fuels can follow different successional patterns. Changes in fuel quantities are better documented in lodgepole pine forests than perhaps for any other species.

Quantities of forest floor litter comprising foliage, bark flakes, twigs, and stems less than about 1 inch in diameter remain fairly constant over time while crown canopies are closed (Alexander, 1979; Jeske and Bevins, 1979). Small oscillations in litter loading occur (Fahnestock, 1976) probably due to the variable effects of wind and snow on the shedding of dead and live crown material.

Shrub and herbaceous understory fuels have been reported to vary from 0 to 8 tons/acre (Alexander, 1979), but lodgepole pine forests characteristically support small quantities of understory vegetation (table 2). Quantities vary by site (Trappe and Harris, 1958) and species composition. High loadings of understory fuel are primarily comprised of shrubs. Changes in understory biomass apparently depend on site conditions and species existing before disturbance (Lyon and Stickney, 1976; Habeck, 1976), as well as on the nature of disturbance. On mesic sites, biomass of herbs and shrubs tends to peak during early stages of stand development and to decrease after that.

Forest floor duff (fermentation and humus layers) increases with time since disturbance by fire. The rate of increase levels off when a balance between accretion and depletion is reached. Depletion is caused by decay and occurrence fires. The time required for duff accumulation to reach equilibrium is difficult to measure because of the confounding influence of low-intensity fire. It may occur soon after 100 years as observed along the Colorado Front Range (Alexander, 1979) or after 300 years as observed in Yellowstone National Park (Romme, 1980).

Duff depths in the Northern Rockies typically range from 0.2 to 1.6 inches (0.5 to 4 cm) (table 3) and accumulations appear to be uninfluenced by aspect (Brown and See, 1981). In Colorado, however, Alexander (1979) and Zimmerman (1982) reported 3 to 4 inches (9-10 cm). Duff loadings corresponding to these depths range from 3.3 to 26 tons/acre based on a characteristic bulk density of 9 lb/ft^3 (Woodard and Martin, 1980; Brown 1974).

In terms of fire behavior, the most significant fuel component in lodgepole pine forests is dead, woody material. Large fuel (pieces greater than 3 inches in diameter) makes up most of the dead material. In unlogged stands, quantities of large fuel typically range from 0 to 20 tons/acre (table 3), with a maximum of 60 to 90 tons/acre possible after downfall of a completely killed stand (Brown, 1975). Stands rated high risk in the Forest Service, Northern Region contained twice the large fuel loadings as other stands. Large fuel loadings were greater on north aspects than south aspects but did not vary significantly with elevation (Brown and See, 1981).

Table 3. – Fuel loadings based on planar intersect sampling of timber stands on National Forests in the Northern Region (Source: Brown and See, 1981).

	Location			
Fuel	Eastern Mont. (3,400 samples)		Western Mont., Idaho (4,172 samples)	
	mean	median	mean	median
Duff depth, inches	1.1	0.8	1.1	0.7
Woody material >3 inch, tons/acre	13.9	4.7	14.4	4.2
Total woody material tons/acre	16.0	7.0	18.0	8.0

Fuel succession in lodgepole pine is exemplified by lack of consistent patterns. In figure 3, median large fuel loadings were normalized using the maximum loading for each of three studies. Loadings of down woody fuel from northern Idaho and western Montana increased continuously with age. In Glacier National Park (Jeske and Bevins, 1979), such fuel loadings decreased until stands were about 100 years old, then they increased. Romme (1980) observed a similar pattern in Yellowstone National Park but the increase began at a stand age of about 200 years. In the Selway-Bitterroot Wilderness, Idaho, the loading trend was the reverse of that in Glacier National Park. In lodgepole pine on the Colorado Front Range, Alexander (1979) found no consistent pattern in loading and stand age.

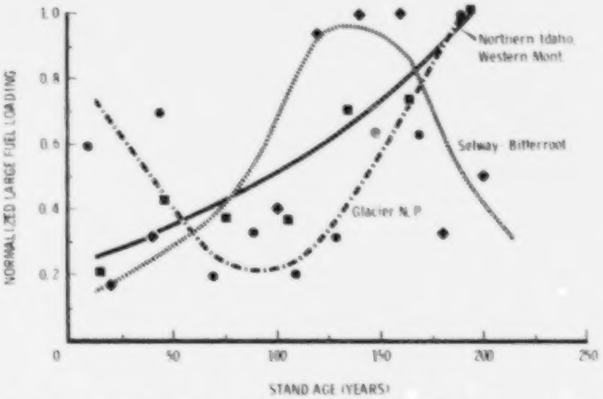

Figure 3. – Normalized loading of large downed woody fuel in lodgepole pine stands of varying age from three studies.

Fuel succession for lodgepole pine (and probably other species) shows two trends: (1) fuel quantities are usually high as stands become overmature, but (2) fuel quantities cannot be predicted from age alone in young immature or mature stands.

Fuel variation in younger stands relates to the size of trees killed by previous fire and the interval until the next fire. High loadings in the juvenile period result from downfall of dead trees from the previous stand. Considerable time may be required for trees from the previous stand to decay and settle into the forest floor. If fire consumes most of the downfall during the juvenile period, the next stand will have much smaller downed fuel loadings during the juvenile period.

Fire- or beetle-killed lodgepole pine begin to fall 2 to 5 years after dying; most trees will be down in 15 years (Lyon, 1977; Flint, 1924). Some large-diameter trees will stand longer. This pattern supports fire specialists who contend that fire hazard in lodgepole pine peaks 25 years after a burn (Lyman, 1945). In 25 years most fire-killed trees would have become surface fuel lying in contact with crowns of regenerating lodgepole pine. The same fire specialists believe that the hazard declines 50 percent from its peak in 35 years and returns to a moderate level some 85 years following the fire. Mason (1915) suggests that fire-killed timber decays in 60 to 120 years. This agrees with Alexander's (1979) study that shows loadings of rotten large fuel to be greatest in stands 40 to 100 years of age.

Potentials for high-intensity fire are greatest when growth of conifers creates crown fuels in close proximity to large accumulations of dead woody fuel. This condition can occur twice during the life of a stand. The first critical period occurs during the juvenile stage as described above. A reburn during this period may consume most of the woody fuel so that the ensuing stand develops with a low fire behavior potential. The second period occurs when the lodgepole pine stand begins to break up and accumulates dead surface fuels in an understory of developing spruce or fir. Stand age for the second period depends on longevity and can vary from 100 years (Trappe and Harris, 1958) to as much as 400 years (Romme, 1980).

Hazard Evaluation

Fire hazard in lodgepole pine stands varies with the development of the stand (Brown, 1975). In young, dense stands and in overmature stands with an understory of shade-tolerant conifers, the hazard of fire is high. In moderately dense to open mature lodgepole pine the fire hazard is low. This is an advantage for a seral species because a fire in an overmature stand will kill the shade-tolerant understory species and provide a seedbed for regeneration of lodgepole pine. A similar fire would kill a dense, young stand, but the fewer cones at that time would produce less, resulting in lower stocking (Brown, 1975). Fire history studies have indicated that understory fires sometimes killed understory species without damaging the lodgepole pine overstory.

Over the past 10 years several methods have been developed for appraising fuels, fire behavior, and hazard. Stylized fuel models used in conjunction with the National Fire Danger Rating System (NFDRS) or the Fire Behavior Prediction System (FBPS) are appropriate for broad resolution (Anderson, 1982). Lodgepole pine levels are usually modeled as follows:

	Model Designations	
	NFDRS	FBPS
Timber group, normal fuel accumulations; low flame lengths	H, R	8
Timber group, heavy fuel accumulations, greater intensities	G	10
Slash	I, J, K	11, 12, 13

A photo series for appraising nonslash downed woody fuels (Fischer, 1981) and residues (Maxwell and Ward, 1976) in the lodgepole pine type is an easy-to-use, site-specific method. It consists of photographs of varying quantities of fuel and descriptions of fuel loadings, stand descriptions, and fire behavior ratings. Fuels observed in the field are compared to photographs for making appraisals.

The greatest resolution in appraisals is provided by inventorying existing fuel quantities or predicting crown weights (Brown and others, 1977). Rates of spread and intensities are then predicted from the fuel quantities and can be further subjected to principles of decision analysis to produce estimates of expected burn areas (Hirsch and others, 1981; Puckett and others, 1979). Hazard also can be classified based on relationships between the Canadian Fire Weather Index and field measurements of rate of spread and intensity (Lawson, 1973; Quintilio, 1972).

Fuel inventory coupled with fire behavior modeling is the most technically elaborate technique for appraising the effects of management actions on fuel and fire behavior. For example, in a study of alternative harvesting practices in lodgepole pine, conventional logging resulted in fireline intensities one year after cutting that were six times greater than in intensive residue removal (everything larger than a 3-inch diameter and 8-foot length removed) (Brown and Lotan, 1982). Intensities for broadcase fire on clearcuts with conventional logging exceeded 500 Btu/s/ft, often considered an unacceptable hazard, for windspeeds greater than 10 mi/h. After 5 years, however, intensities were only slightly greater under conventional logging due to needle drop and settling of slash. In two separate studies of fire hazard in precommercially thinned lodgepole pine, potential rate of spread was increased 3 to 5 times by thinning (Hawkes and Lawson, 1980, Alexander and Yanick, 1978).

Fire behavior modeling must be applied with awareness of limitations in the model. For example, the Rothermel (1972) spread model assumes uniformly distributed fuels and pertains only to a propagating flame front supported by fine surface fuels. Fire behavior caused by combustion of large fuels is not modeled. Although fire behavior modeling allows managers to appraise fire potentials quantitatively and consistently, experienced judgement is essential to proper interpretations.

FIRE ECOLOGY

Fire Effects on Succession

Lodgepole pine is an aggressive seral species that readily establishes itself on disturbed areas, including burned areas (Clements, 1910; Mason, 1915; Horton, 1953; Smithers, 1961). Bare, mineral soil provides the best seedbed for lodgepole pine. This fact is readily observed on disturbances such as roadsides, powerlines, or on most clearcut or burned areas.

Because of its ability to grow on almost any forest site, lodgepole pine occurs in a wide range of forest types. It therefore displays a variety of successional roles that are controlled partly by the environmental conditions and partly by competition from associated species adapted to the site. Successional variation can be defined in four basic successional roles for lodgepole pine (Pfister and Daubenmire, 1975):

1. Minor seral. A component of young even-aged stands being rapidly replaced by shade-tolerant associates in 50-200 years.
2. Dominant seral. The dominant cover type of even-aged stands with a vigorous understory of shade-tolerant species that will replace the lodgepole in 100-200 years.
3. Persistent. The dominant cover type of even-aged stands with little evidence of replacement by shade-tolerant species.
4. Climax. The only tree species capable of growing on a particular environment, i.e., self perpetuating.

Some persistent stands of lodgepole pine are the result of repeated fires that have eliminated seed sources of other species (Tackle, 1961; Lotan, 1976; Lotan and Perry, 1983). Other stands are pure lodgepole pine because site conditions are such that no other tree species can survive (Despain, 1973; Moir, 1969; Franklin and Dryness, 1969).

Without periodic fire lodgepole pine tends to be replaced by more shade-tolerant species such as Douglas-fir, Engelmann spruce, and subalpine fir. In fires in mixed stands the proportion of lodgepole pine will increase with each recurring fire. Only western larch approaches the tenacity with which lodgepole pine recolonizes a disturbed site.

Lodgepole pine succession is regulated by several biotic and abiotic factors. Some of the major biotic factors regulating this succession are: the growth characteristics of lodgepole pine itself, the mountain pine beetle, and dwarf mistletoe. Fire is an important abiotic factor in successional regulation. Important characteristics of lodgepole pine that contribute to its aggressive capability to recolonize a site are a readily available supply of seed and rapid juvenile growth.

Extensive stands of lodgepole pine are found in the Douglas-fir and spruce-fir climax series (Pfister and Daubenmire, 1975; Wellner, 1975). In these series extensive areas have burned during severe fire weather.

The effects of low-intensity fires in lodgepole pine stands depends upon availability of seed and amount of duff removed. In pure stands of lodgepole pine, nonserotinous cones provide seed for surface burns. Surface fires do not open the serotinous cones in the crown. Most stands have sufficient open-coned trees to provide abundant seed (Mason, 1915; Lotan, 1970). In mixed stands the composition of regeneration is generally similar to that of the overstory, but resistance to fire will favor some species over others.

High-intensity fires in pure lodgepole pine stands usually result in a new stand of pure lodgepole pine. In this case the high biotic potential in seed stored in serotinous cones is of great importance in the establishment of extensive areas of pure, dense, lodgepole pine. Seed is accumulated for decades.

Quantities of seed equal to 10 years annual production is available for recolonizing a site (Lotan, 1975a, 1976). Millions of sound seed per acre are often available. This abundant supply of seed combined with rapid juvenile growth make the species a formidable competitor in stand establishment.

Lodgepole pine, when disturbed, will colonize open sites with mineral soil seedbeds and grow faster than most other conifers invading the site. Depending on site conditions, lodgepole pine will continue this growth for 30 to 80 years before it begins to slow down. After about 80 years, the growth rate of lodgepole pine will slow significantly while the growth rate of more shade-tolerant species in the understory increases. At about this time (80 years), the understory tree species will begin to overtop the lodgepole pine (Eis and others, 1982).

The influence of insects, disease, and fire often interrupt this succession and prevent its progression to climax vegetation. In the absence of fire or other disturbances, and except where it is climax or persistent, lodgepole pine will decrease in the ecosystem because of its inability to compete with shade-tolerant tree species.

The effects of fire intensity on stand establishment, as discussed by Brown (1975) and Muraro (1971), can be briefly stated as:

High Intensity Fire

1. Creates good seedbed conditions on mesic and wet sites, and when seed is abundant, dense stands are established. On dry sites, however, low stocking can result because of poor moisture conditions.
2. Crown fires usually cause maximum release of stored seed. In surface fires with considerable crowning, mineral soil is exposed, serotinous cones open, and if seed is abundant a dense stand results. Occasionally, severe crown fires consume up to ½-inch-diameter fuel, destroy much of the seed supply, and a lower density stand results.
3. When seedbed conditions, seed supply, soil moisture, and other factors are favorable for stand establishment, extremely high stocking (leading to stagnated stands) frequently results.
4. Competition from understory vegetation, particularly grass, can decrease stand density even if other factors influencing establishment are favorable.

Low-Intensity Fire

1. Moisture content of duff is an important factor in determining level of stocking. When duff is dry a low-intensity fire will expose mineral soil, resulting in a high level of stocking. When duff is moist, fire will expose less mineral soil, resulting in poor seedbed conditions and low stocking.
2. Mortality may be minimal or sporadic. Sometimes widely spaced stands result. In time, two-aged or three-aged stands can develop.
3. In stands of mixed species, the survival of lodgepole pine depends on its fire resistance relative to other species as well as the seed potential of all species. Post fire species composition, age structure, and density of mixed stands vary considerably, depending upon fire characteristics and many other interrelated factors.

Though lodgepole pine is a fire-adapted species, fire management must carefully consider the dynamic relationships occurring within different lodgepole pine communities. Fire may occur at various points during succession and have different effects.

Fischer and Clayton (1983) gave a generalized depiction of forest succession for cool habitat types usually dominated by lodgepole pine (fig. 4). The climax forest indicated within the circle is usually not reached. In most of these forests, fire cycles maintain the dominance of lodgepole pine. The short-lived herb/shrub stage often provides forage for livestock or big game, but fires are not likely in this stage. In Eastern Montana, the Cross Creek Fire burned around a logged area that was in this stage (personal observation, 1984). Fischer and Clayton's

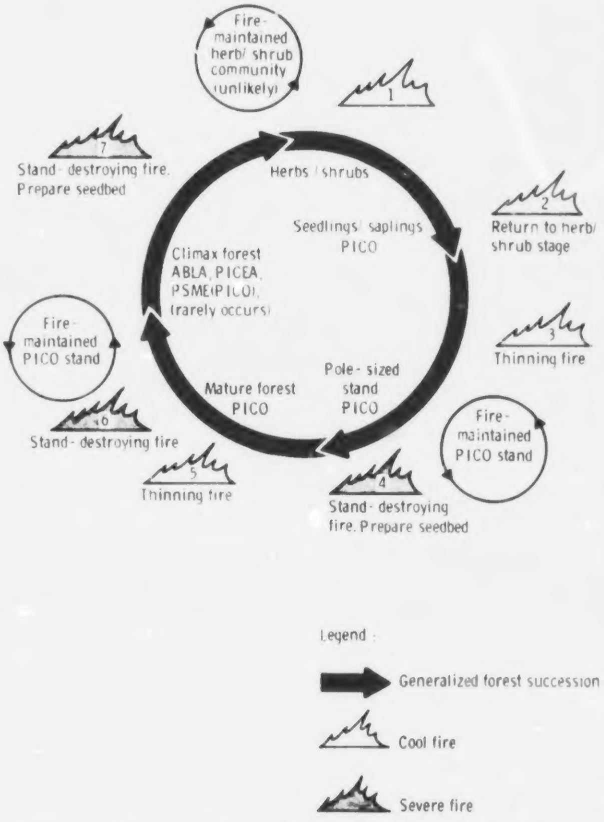
Fire-maintained herb/ shrub community (unlikely)
1
7
Stand-destroying fire. Prepare seedbed
Herbs / shrubs
2
Return to herb/ shrub stage
Seedlings/ saplings PICO
Climax forest ABLA, PICEA, PSME(PICO), (rarely occurs)
3
Thinning fire
Fire-maintained PICO stand
Pole-sized stand PICO
Mature forest PICO
6
Stand-destroying fire
Fire-maintained PICO stand
5
Thinning fire
4
Stand-destroying fire. Prepare seedbed
Legend :
Generalized forest succession
Cool fire
Severe fire

Figure 4. – Forest succession in cool habitat types usually dominated by lodgepole pine.

summary is an excellent reference for details on fire as an ecological factor for forest habitat types in the northern Rocky Mountains.

Other Factors

In addition to fire, climatic and edaphic characteristics promote pure stands of lodgepole pine. In much of the commercial lodgepole pine in the Rocky Mountains, the climate during the growing season is reasonably similar. Although precipitation decreases from west to east, the proportion of summer rainfall increases. Overall climatic generalizations in the lodgepole pine region are: snowfall is heavy and supplies the major portion of soil water used for growth in early summer; winter temperatures are cold; summer, especially in July and August, has relatively low rainfall; and in many areas, especially in basins and other cold-air pockets and at high elevations there is no true frost-free period (Lotan and Perry, 1983). Lots of exceptions occur. For example, in Colorado summer precipitation is more abundant after a dry season in May and June.

When species are viewed on an elevational gradient, lodgepole pine often occupies the middle, moderately mesic environment. Often where it is climax, the soil moisture or other site conditions are extreme: either seasonably ponded soils or well drained-droughty sites (Pfister and Daubenmire, 1975). Lodgepole pine often occurs on sites that are droughty or where other species are unable to grow (Moir, 1969; Stephens, 1966). In other areas, lodgepole pine is tolerant of high water tables or flooding (Minore, 1968; Cochran, 1972), and extreme frost pockets as in central Oregon.

Although lodgepole pine occurs on a wide range of soils, the species does best on soils derived from granite, shale, and course-grained lavas (Tackle, 1961; Despain, 1973). The effects of soil properties and soil moisture result in local situations favoring lodgepole pine over other species.

Lodgepole pine often grows under nutrient conditions less than optimal for other conifers, with nitrogen the most limiting element. It is often the only conifer that will grow on extremely infertile soils (Stephens, 1966, Despain, 1973). Near West Yellowstone, Mont., the establishment of lodgepole inversely related to the amount of nitrogen and potassium in soils (Stermitz and others, 1974). It simply grows where other conifers cannot.

Lodgepole pine may occupy a low nutrient niche, either through an extremely low nutrient requirement (van den Driessch and Waring, 1966) or an ability to extract nutrients that are unavailable to other species (Lewis and Eisenmeuser, 1948; Stone and Fischer, 1969). Despain (1978)[1] has suggested that lodgepole pine stands may have evolved to maintain a low soil nutrient status and thus avoid direct competition with other, more nutrient-demanding species.

Higher accumulation of nutrients in the forest floor has been observed in lodgepole pine stands than in other pine-dominated ecosystems (Jenny and others, 1949; Moir and Grier, 1969). Fahey (1983) found that nutrient returns in annual litter fall are much lower in lodgepole pine ecosystems than in most forest types that have been studied because of low litter fall mass and low element concentrations in leaf litter. The accumulation of mass and nutrients in the forest floor was high, considering the low rates of litter deposition. Thus, residence times for organic matter and nutrients were considerably longer than those which have been calculated for pine forests from warmer and/or more moist climates.

Cone Serotiny

Although the thin-barked lodgepole pine is fairly susceptible to fire, the serotinous cone habit enables it to regenerate large areas after disturbance. The persistence of a lodgepole pine forest cover over such vast areas is directly attributable to its ability to disperse vast amounts of seed upon a freshly prepared seedbed. Millions of sound seed per acre are stored within the serotinous cones in mature stands (Lotan, 1967, 1968).

This ability to regenerate vast areas is not due to the serotinous cone habit alone. Seed viability, germinative energy, rapid juvenile growth, prolific seed production, and ability to survive a wide variety of microsite and soil situations all contribute to its aggressive nature in these situations (Haasis and Thrupp, 1931; Critchfield 1957, 1980; Lotan 1975, 1976; Lotan and Perry 1983; Illingworth 1975). Of all these traits cone serotiny is a key factor because of its potential for storing large numbers of seeds that can be released all at one time upon a freshly prepared seedbed.

Because of its impact upon stand regeneration, the serotinous cone habit must be considered in any management program involving lodgepole pine in much of the range of lodgepole pine. The proportion of serotinous-coned type trees in a stand varies considerably (Lotan, 1975). Bates and others (1929) pointed out, however, that fire is not absolutely necessary to open serotinous cones. Serotiny can be broken from heat near the soil surface during summer weather (Crossley, 1956; Lotan, 1964b).

Lotan discussed variability of cone serotiny in the previous lodgepole pine symposium in Pullman, Wash. (Lotan, 1975a) and at a Tall Timbers Meeting in Missoula, Mont. (Lotan, 1976). Critchfield (1957) reported general variability in his descriptions of the four subspecies of lodgepole pine: Critchfield showed us that Rocky Mountain and Mendocino Plains stands tend to bear persistent, asymmetrical, obliquely attached, hard, and serotinous cones. Cones on lodgepole pine in the Sierra Nevada are deciduous, symmetrical, fragile, and consistently open. Critchfield considered cones of shore pine along the west coast, in the Blue Mountains of Oregon, and in the Cascade Mountains as intermediate in cone traits.

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[1] Despain, Don G. 1978. (Personal communication) Yellowstone National Park, WY.

Although Rocky Mountain populations have been considered to be the serotinous-coned type, Lotan's studies (1975a) showed that variation does occur even in Rocky Mountain stands. Elevational clines were found in local areas (Colville National Forest), but throughout the study area these relationships were maintained. The range of elevations sampled throughout the study was from 2,100 ft (~ 640 m) to 10,200 ft (~ 3090 m). The proportion of serotinous-cone type trees within in a particular stand ranged from 0 to more than 80 percent throughout the Northern Rocky Mountains.

Variation within a stand is usually quite low. Often variation within a drainage is low, with sharp boundaries between populations. It appears that the base population is open-coned, with the closed-cone trait occurring as swarms within the base population.

Critchfield (1957) suggested fire as the selective agent primarily responsible for the evolutionary divergence in one habit between Rocky Mountain and Sierra Nevada populations. The Rocky Mountains are known for stand-replacing fires at least in some years compared to the Sierra Nevada where stands have commonly burned with light surface fires. Further, Lotan (1967) compared serotiny in an even-aged stand of recent fire origin with a contiguous uneven-aged stand. The even-aged stand would have originated primarily from seed released from cones opened by fire. The uneven-aged stand regeneration would have been established from an annual seedfall from open-coned trees. Fifty-eight percent of the even-aged stand had serotinous-cone type trees compared to only 38 percent of this type tree in the uneven-aged stand.

It is difficult to develop a relationship between fire regimes and cone serotiny over broad areas, however, because of the many confounding variables involved. Perry and Lotan (1979) developed a hypothetical model of fire selection for cone serotiny that indicated that gene frequencies for the closed cones was particularly sensitive to stand-replacing fires while accounting for the large population of open-coned type trees, sampled in Lotan's (1975a) study. Muir and Lotan (In press) collected data on the Bitterroot National Forest in Montana that substantiated the hypothetical model – their study showed that the degree of cone serotiny depends greatly upon the nature of the last disturbance, and that a large proportion of these trees are open-coned.

In the Rocky Mountains where cone serotiny appears to be the most common, lightning-caused fires have no doubt been a strong selection force for the closed-cone habit. The serotinous cone habit in lodgepole pine is an "adaptive trait," i.e., one that facilitates survival and/or reproduction of its carrier. We must be careful not to presume selection because traits enhancing survival during fires may also enhance survival during stress from other environmental factors.

Prediction equations have been developed to estimate seed stored in closed cones of the canopy (Lotan and Jensen, 1970; Lotan, 1975a). This knowledge, together with information on seed: seedling ratios for particular habitat types, topographic situations, and climates, helps to explain much of the variation in natural reproduction in lodgepole pine (Lotan and Perry, 1983). Seed from open cones can be estimated from conventional seedtraps.

Natural Regeneration

Lodgepole pine is usually considered to be a prolific seed producer. Good seed crops occur at 1-3 year intervals, with light crops intervening (Tackle, 1961; Lotan and Perry, 1983). Lodgepole pine may start bearing cones at less than 10 years of age. Because of small seed, lodgepole pine seeds travel further than many others, but usually not over 200 ft (60 m).

The viability of lodgepole pine seed remains relatively stable even in old cones on trees for many years. Released seeds do not remain viable in appreciable numbers longer than one year.

Germination under field conditions is highly variable, depending on climate conditions and seedbed type. Experience in the Rocky Mountains has generally indicated that mineral soil seedbeds are superior for germination (Tackle, 1961 rev.; Lotan, 1964a; Prochnau, 1963; Blake, 1976). Germination is poor with maximum temperatures below 60° F and seems to be optimum in the range of 70° to 80° F, with fluctuating diurnal temperatures (Bates, 1930; Hassis and Thrupp, 1931). Seedling germination is rapid following snowmelt when both day and night temperatures are favorable (Lotan, 1964a). When soil moisture is sufficient, germination of seed is apparently unaffected by seedbed type (Fisher, 1983; Minore, 1972).

Disturbed mineral soil generally results in not only the best germination but also the best seedling survival (Lotan, 1964a; Alexander, 1966; Lotan and Dahlgreen, 1971; Lotan and Perry, 1977b; Schmidt and Lotan, 1980; Schmidt, 1982), although disturbed duff or undisturbed duff that is not over one 1 inch thick may also give good results, particularly on moist sites (Tackle, 1956; Ackerman, 1957). Stocking is generally poor on deep duff and ash surfaces. The mere presence of lodgepole pine on various habitat types implies a history of site disturbance.

Seedling mortality varies greatly with soil type and seedbed condition. Survival is enhanced by good water-holding capacity, but is reduced by rising amounts of nitrogen and potassium, which foster competition from grass and forbs (Stermitz and others, 1974). New lodgepole pine seedlings are vulnerable to drought because of a relatively weak, slowly developing root system. Noble (1979) reports one-season rooting depths of less than 4 inches. Shallow roots is a major factor contributing to mortality on both mineral soil and undisturbed areas. Lotan (1964a) noted significantly longer roots on prepared seedbeds compared to control plots with heavy grass competition. This may account for the belief that lodgepole pine seedlings have difficulty in competing with other vegetation, and grass provides the most competition.

Drought is a common cause of mortality among first-year lodgepole pine seedlings (Lotan, 1964a). In greenhouse studies, watered seedlings receiving less than 2 inches per month had low survival (Sheppard and Noble, 1976; Perry and others, 1978).

It is unlikely that nutrient deficiency is a serious cause of mortality in lodgepole pine. DeByle (1980) showed nutrient levels on different prepared seedbeds were greater or similar to undisturbed forest soils. Also by the second year, seedlings have presumably developed a root system and mycorrhizal associations that exploit the site efficiently.

MANAGEMENT IMPLICATIONS

Though lodgepole pine is adapted to fire, fire management must carefully consider fire and ecosystem relationships. Variability is common in lodgepole pine. Although the species is usually seral and even-aged, it is not uncommon to find multiaged stands. Insects and disease greatly impact these forests, particularly the mountain pine beetle and dwarf mistletoe. Fires may occur at any point in the history of the stand and the effect of fire will vary greatly depending upon characteristics of the fire and the condition of the stand.

The Use of Natural Fire

Because of its widespread occurrence, lodgepole pine is frequently the forest of wilderness, national parks, or other areas managed for natural ecosystems. Here natural processes are allowed to function with a minimum of interference by man. Fires ignited by natural means such as lightning are considered natural processes. Most authorities agree that, with due consideration for human life, property, and resources outside natural ecosystems, lightning fires be allowed to burn under prescribed conditions.

There is some argument and precedent for using prescribed fire with deliberate, scheduled ignitions in parks and wilderness. In some areas 50 to 75 years of effective fire control has altered the historical fire regime thus resulting in unusual amounts of fuel and stand conditions. These areas are then susceptible to unusual fire behavior. The use of prescribed fire ignited by trained professionals and under carefully controlled conditions would permit subsequent use of natural fires without high fire hazard. Also some designated natural areas are too small for naturally ignited fires to be effective. The National Park Service currently uses prescribed fire. The USDA Forest Service is now studying the possibility of conducting prescribed burns in wilderness.

Fire Management for Multiple Use

In most lodgepole pine forests, use of prescribed fire has been limited to slash disposal and site preparation in connection with clearcut logging (Fischer and Clayton, 1983). Many of these lodgepole pine forests are seral stands in the Douglas-fir, Engelmann spruce, and subalpine fir habitat series. Lodgepole pine, spruce, and fir have relatively low fire resistance, and all are susceptible to fire damage. Further, in safe fire weather these forests are hard to burn. Burning must be done under dry conditions, therefore prescriptions must be written for a rather narrow prescription "window." Broadcast burning is possible, and when properly used, is an environmentally and economically sound management tool (Lotan and Perry, 1977a; Zimmerman, 1982; Brown and Lotan, 1982; Lotan, 1982; Schmidt, 1982).

Although several even-aged silvicultural systems may be used to regenerate lodgepole pine, the general practice is to clearcut to obtain natural regeneration (Lotan, 1975b; Lotan and Perry, 1983; Alexander and others, 1983). Lodgepole pine is susceptible to windthrow when the stand is partially cut. Partial cutting hampers the use of fire because of lodgepole pine's susceptibility to fire damage. When stands are clearcut, piling and burning is commonly practiced, but broadcast burning is sometimes used (Lotan and Perry, 1977a; Zimmerman, 1982). Broadcast burning not only increases the yield of forage for big game and livestock, it was the preferred site treatment when wildlife, water values, and esthetic quality were considered (Benson, 1982).

Slash disposal methods are discussed in the proceedings of the previous symposium on lodgepole pine (Lotan, 1975b) and in the summary publication by Lotan and Perry (1983). A summary is provided here. Slash disposal should not be conducted solely to reduce the fire hazard because improper handling of slash can result in considerable loss of seeds contained in closed cones. Seed losses may reach 90 percent or more but can be kept below 25 percent with proper slash handling techniques (Lotan and Perry, 1983). Timing is important. Losses may be high, particularly if treatment of slash is prolonged until after germination. Feller (1982) reported some disparity amongst published reports over desirability of slash-burning in lodgepole pine, but broadcast burning is not detrimental if prescriptions are carefully done (Brown and Lotan, 1982; Zimmerman, 1982; Lotan and Perry, 1977a). Soil is damaged only under large piles that should not represent more than 25 percent of the area. This is currently being investigated in a cooperative study among the scientists at the Northern Forest Fire Laboratory in Missoula and the University of Idaho. Muraro (1971) developed a prediction system to control the reduction of duff and slash fuel and predict the amount of mineral soil exposed.

Significant differences in seed:seedling ratios may be obtained with various seedbed conditions (Lotan and Perry, 1983).

Seedling survival is best on bare mineral soil, but some protective cover may be beneficial, depending upon slope, aspect, and location (Lotan, 1964a, Alexander 1966, Lotan and Dahlgreen 1971, Lotan and Perry 1977a). Disturbed duff and undisturbed duff less than one inch (2 to 3 cm) will yield good regeneration and survive on moist sites (Tackle, 1956; Ackerman, 1957). Deep ash makes a poor seedbed.

Some cover may be beneficial on extremely droughty sites (Lotan and Perry, 1983). Tackle (1956) found that stocking under logging slash less than 1 ft (30 cm) was as good as bare, mineral soil. Kovalchik and Blake (1972) found that areas treated with a roller chopper had as many seedlings as areas that had been piled and burned. Roe and Schmidt (1964) found a moderate vegetative cover to be beneficial.

Slash hazard can be abated and duff can be reduced to prepare the seedbed for natural regeneration, using broadast burning when prescriptions and execution are carefully done. When environmental consequences are considered broadcast burning is a treatment that approximates natural processes (Lotan and Perry, 1977a; Schmidt and Lotan, 1980; Benson, 1982).

There are only a few guides for broadcast burning in lodgepole pine and there is much variability to consider. Zimmerman (1982) developed preliminary guides for broadcast burning lodgepole pine slash in Colorado. Quintilio (1970, 1972) developed preliminary guides for prescribed burning in southwestern Alberta.

Zimmerman's recommendations are:

Temperature	54-70°F (12-21°C)
Relative Humidity	25-40 percent
Windspeed	0-6 m/h (1-10 k/h)
10-hr. Fuel Moisture	9.5 to 12.5 percent

These were the conditions that worked for Zimmerman. He realized that different weather conditions might also be successful. In fact he has completed successful burns with wind speeds as high as 18 mi/h (30 km/h). Quintilio's guides relate rate of head-fire spread and depth of burn to components of the Canadian Forest Fire Weather Index System.

Adams (1972) showed good stocking using broadcast burning, but did not provide conditions for burning. Our own studies at Union Pass, Wyo., showed excellent results using broadcast burning when compared to other logging and post-logging treatments (Benson, 1982). We burned in the spring only two to three weeks following snowmelt. Fuel moistures were higher than prescribed but winds were a constant 15 mi/h (24 km/h). Burning was conducted on a June evening between 1900 and 2200 hours. Ignition followed a pattern from the center to the edges of the unit; a smoke column was created, and the strong, steady breeze kept it at a 45 degree angle. Some adjacent timber was scorched where heavy concentrations of slash had been windrowed (Brown and Lotan, 1982). As a general rule, burning in lodgepole pine has to be done with fairly dry fuel moistures or with a steady breeze. Some fire management officers successfully burn the type, but their methods have not been published. For maximum exposure of mineral soil, Shearer (1975) recommends burning in October. His relationship of duff reduction to duff moisture content is shown in figure 5.

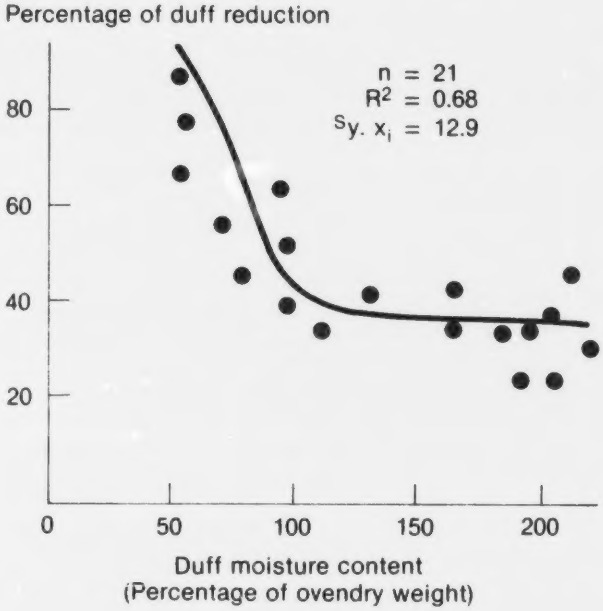


Figure 5. – Duff reduction related to moisture content of the lower half of duff layer (from Shearer, 1975).

Harvesting over-mature stands under current utilization standards leaves large quantities of logging debris (Benson, 1982) which is why reduction of fire hazard has always been a prime consideration in site preparation. Demand for firewood has changed total utilization in many areas and new techniques and better utilization will no doubt lessen slash hazard, but nevertheless, fire will remain useful in managing lodgepole pine far into the future. With the variability in both understocking and overstocking of the species, much can be gained by proper handling of logging slash.

Large areas of lodgepole pine have been harvested and the potential for harvesting even more is great. Lodgepole pine is one of the most under-utilized species in the Rocky Mountains (Koch, this proceedings).

Once these stands have been regenerated, we must protect a rather large investment, particularly the prevention of stand-destroying fires over large areas. One solution is to create a fully regulated forest with a good distribution of age classes. This will minimize the danger of having large, extensive stands of trees that are all of the same fire hazard. This same strategy will assist greatly in minimizing insect or disease pandemics.

The Use of Fire in Controlling Insects and Disease

The two most serious pests of lodgepole pine are the dwarf mistletoe and the mountain pine beetle. It is generally accepted that fire has played a major role in the distribution and abundance of these two damaging agents in lodgepole pine forests (Amman, 1975; Alexander and Hawksworth, 1975, 1976; and Amman and Cole, 1983). Certainly large, extensive stands of pure lodgepole pine regeneration are relatively free of these agents for decades following severe wildfires (Lotan 1975a; Lotan, 1976), but these same areas will become susceptible as they mature. The use of fire and/or harvesting techniques can influence the impact of pests.

Dwarf Mistletoe

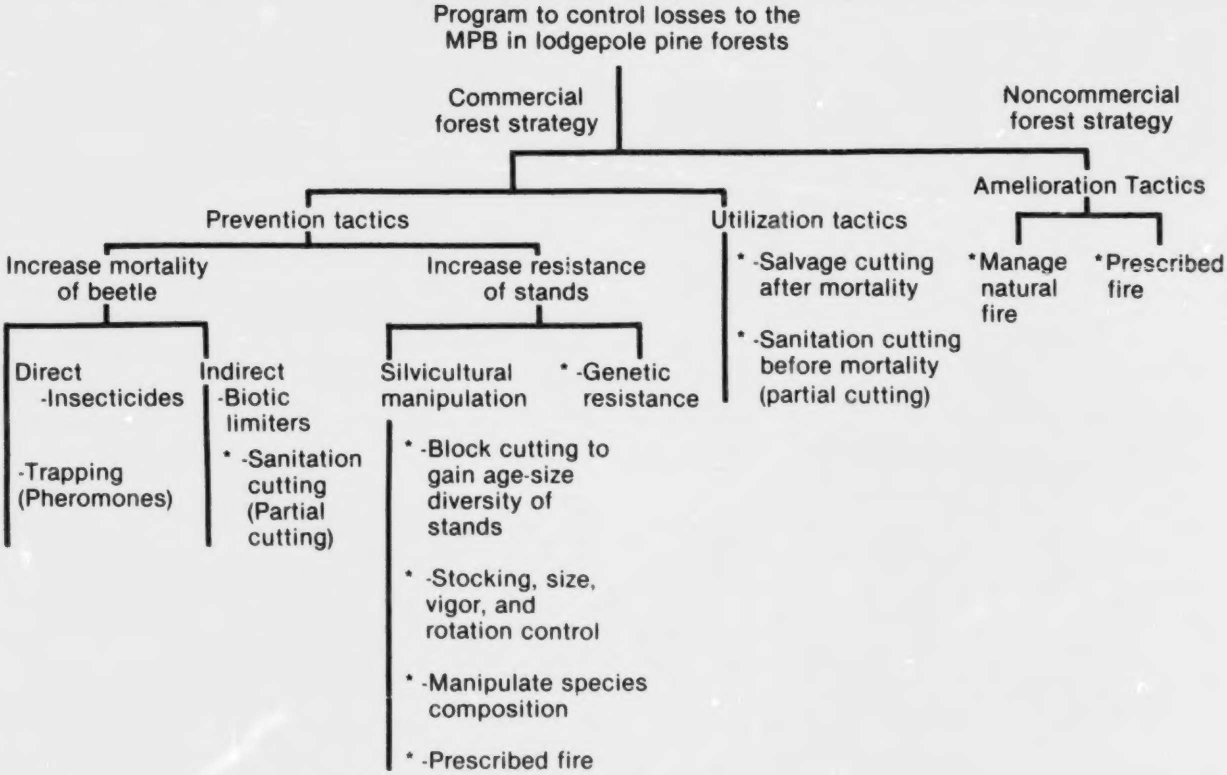
Fire may enhance or disrupt the population of dwarf mistletoe, depending upon current situations and the nature of the fire (Alexander and Hawksworth, 1975). Widespread, stand-destroying fires have a sanitizing effect on infested stands, whereas surface fires or fire burning in a mosaic pattern leave infested trees that lead to further spread of dwarf mistletoe. Wildfire has probably served as a natural check on dwarf mistletoe populations. On the other hand, tree mortality, spike tops, witches' brooms, and resin exudation increase fuels (Beaufait, 1971) and result in greater incidence and intensity of fire. Overall, the decrease in area burned as a result of fire control may have led to an increase in dwarf-mistletoe-infested stands (Kimmey, 1957; Alexander and Hawksworth, 1975; Baranyay, 1970, 1975).

Alexander and Hawksworth (1975) recommended prescribed burning as a supplement to the traditional control of dwarf mistletoe using silvicultural treatments. Prescribed fire can be used to remove groups of infested trees and may be useful where cutting is undesirable such as in wilderness or other reserve areas. Further, prescribed fire can be used in combination with silvicultural treatment. Kimmey and Graham (1960) recommended using broadcast burning to kill unmerchantable trees following clearcutting. The potential for using prescribed fire to reduce the incidence of dwarf mistletoe is great. What is needed is quantitative information for developing prescriptions to meet the desired end.

Mountain Pine Beetle

The mountain pine beetle is the most serious insect pest in lodgepole pine forests. About every 20 to 40 years epidemics sweep through lodgepole pine forests and seriously affect the sustained yield and regulation of managed forests (Wellner, 1978). During these epidemics the beetle kills almost all merchantable trees, which complicates the management of the species. Even in unmanaged forests the beetle kills trees over entire hillsides or canyons, arousing public concern. In addition, reserve areas such as wilderness and parks may become the source of infestation for adjacent managed areas. Further, the fuel that is created by beetle-killed trees creates a serious fire hazard.

Past efforts of direct chemical control have proven futile (Amman and Baker, 1972). The beetles simply multiplied faster than areas could be treated. Thus current strategies for control of the beetle involve breaking up the large stands of lodgepole pine by an admixture of age classes and alternate tree species (Roe and Amman, 1970; Amman and Baker, 1972; Cole, D. M., 1978; Cole, W. E., 1978). D. M. Cole (1978) suggested several strategies to accomplish this, including the use of fire (fig. 6). Unfortunately, as in the case of controlling dwarf mistletoe, quantitative relationships of fire and the beetle have not been established. There is much research to be conducted. In the meantime, we know that establishing a new stand will curtail beetle populations because mountain pine beetles are not active in young, small diameter trees. We also know that beetle epidemics created large amounts of jack-strawed fuel that often results in large, extensive fires (Lotan 1976).


Program to control losses to the MPB in lodgepole pine forests
Commercial forest strategy
Noncommercial forest strategy
Prevention tactics
Utilization tactics
Amelioration Tactics
Increase mortality of beetle
Increase resistance of stands
* -Salvage cutting after mortality
* -Sanitation cutting before mortality (partial cutting)
*Manage natural fire
*Prescribed fire
Direct
-Insecticides
-Trapping (Pheromones)
Indirect
-Biotic limiters
* -Sanitation cutting (Partial cutting)
Silvicultural manipulation
* -Genetic resistance
* -Block cutting to gain age-size diversity of stands
* -Stocking, size, vigor, and rotation control
* -Manipulate species composition
* -Prescribed fire

*Indicates silvicultural practice is involved.

Figure 6. – Role of silvicultural practices and prescribed fire for controlling losses to mountain pine beetle.

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INFLUENCE OF FIRES, FUNGI AND MOUNTAIN PINE BEETLES ON DEVELOPMENT OF A LODGEPOLE PINE FOREST IN SOUTH-CENTRAL OREGON[1]

R. I. Gara, W. R. Littke, J. K. Agee, D. R. Geiszler, J. D. Stuart, and C. H. Driver

ABSTRACT

Virtually pure lodgepole pine stands form an edaphic climax community over large areas of the infertile "pumice plateau" of south-central Oregon. During our ongoing studies on the dynamics of these forests we developed the scenario that periodic fires create fungal infection courts in damaged roots; in time, advanced decay develops in the butts and stems of these trees. The mountain pine beetle preferentially selects and kills these trees during the flight season. As these outbreaks develop, additional uninfected trees are attacked. In time, the stage is set for subsequent fires as needles drop, snags fall, and logs decay.

INTRODUCTION

Lodgepole pine covers some 3 million acres of commercially important and scenic lands of the Pacific Northwest. The species, *Pinus contorta* var. *murrayana* (Grev. and Balf.) Engelm., has a wide ecological amplitude, and as such, it represents a valuable timber species of the region although its past commercial value has been low. Its positive establishment following fires and its rapid juvenile growth offer promise that the species can be used in short rotation management schemes (Wellner 1973, Cole 1973, Dahms 1973). Besides their potential for timber production, lodgepole pine forests provide vast recreation and wilderness areas (Despain 1973, Litton 1973), important water source areas (Hoover 1973), and range and wildlife habitats (Dealy 1973).

Lodgepole pine was one of the pioneering species to occupy infertile tephra deposits at the close of the last glacial period in the southern Oregon Cascades (Hansen 1946). Franklin and Dyrness (1973) consider the virtually pure lodgepole pine stands to be an edaphic climax community on many sites of this so-called pumice plateau of south-central Oregon. Under certain circumstances the dynamics of these forests are controlled by the interacting effects of fires, the mountain pine beetle (*Dendroctonus ponderosae* Hopk.), and fungal pathogens (Geiszler *et al.*, 1980). The main goal of the research summarized here was to assess the relative roles these ecological events play in the establishment and development of a climax lodgepole pine forest in south-central Oregon.

RESEARCH SITES

Our research sites within the Fremont National Forest and adjacent areas encompassed several discrete fire sites; these areas have been the scene of recurring epidemic infestations of the mountain pine beetle (R. E. Dolph, pers. comm. 1980). These burned sites included: 1) Bald Mt. – a prescribed fire of 1982; 2) Wickiup Springs – a prescribed fire of 1976; 3) Lookout Point – a stand replacement fire that occurred in 1839 and a moderate fire in 1898; and 4) a 1980 fire at Crater Lake National Park that burned near the northern boundary of the park and eventually spread through a climax lodgepole pine stand in the Sharp Peak area of the Park.

All study areas were about 1,800 m elevation with soils derived from Mt. Mazama pumice and ash, which were deposited about 6,600 years ago. The area received an additional tephra deposit from the Paulina Peak eruption ca. 4,000 years ago. Annual precipitation, largely as snow, averages 60 cm. Because of the coarse-textured surface soil and low rainfall, plant species diversity of this pumice plateau is low, and trees, shrubs and herbs are shallow rooted.

The research results summarized below reflect the current status of our knowledge concerning the dynamics of these climax lodgepole pine stands.

RESULTS

Fire Behavior. – Climax lodgepole pine forests are more fuel-limited than other forested communities in the Pacific Northwest. The exceptionally low wood productivity (1-2 $m^3 \cdot ha^{-1} \cdot yr^{-1}$) and leaf area (1-2 $m^2 \cdot m^{-2}$) result in little fuel accumulation, particularly of fine fuels that usually carry the fire. Both prescribed and natural fires in summer months have been observed to spread widely across red fir (*Abies magnifica* var. *shastensis* Lemm.) and ponderosa pine (*Pinus ponderosa* Doug. ex Loud.) forests without entering adjacent climax lodgepole pine stands. Where spread into lodgepole pine stands occurred, it was always along corridors of partially-decayed logs, remnants of a disturbance several decades earlier (Agee 1981). Under the conditions we have observed, fire presence and behavior in lodgepole pine forests is more closely linked to coarse fuel dynamics than to fine fuel dynamics, and thus to the history of past disturbances.

Logs often have higher fuel moistures than associated fuel classes, but the quantity and arrangement of these other fuels are such that they rarely carry the fire. For example, in the

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Crater Lake prescribed fire, litter and fine twig fuel moistures ranged from 4 to 10 percent, but the fuel was too discontinuous to sustain fire spread. The highest dead fuel moisture content (42 percent dry wt.) was measured in the interior of a decayed log, and this was the only fuel that would carry the fire.

Two primary mechanisms are responsible for fire spread along these moist, partially-decayed logs. First, the decayed interior of the log is usually surrounded by a less-decayed rind of sapwood. This allows for reasonable air circulation while the rind helps conserve heat by reducing convective heat loss from the log interior. As the interior portion flames or smolders, the sapwood rind may collapse and be consumed, or may be left as charred residue as the fire slowly moves along the log. The second characteristic of these logs is that rotten wood generally requires less energy to produce the combustible gases required for ignition (Susott, 1982). These physical and chemical characteristics appear to favor partially decayed logs as fire corridors under most conditions. Less-decayed logs would be more likely to burn in years of extended drought when fuel moisture is very low. The result of this typical fire spread pattern is a matrix of burned log corridors with unburned areas in the gaps between logs.

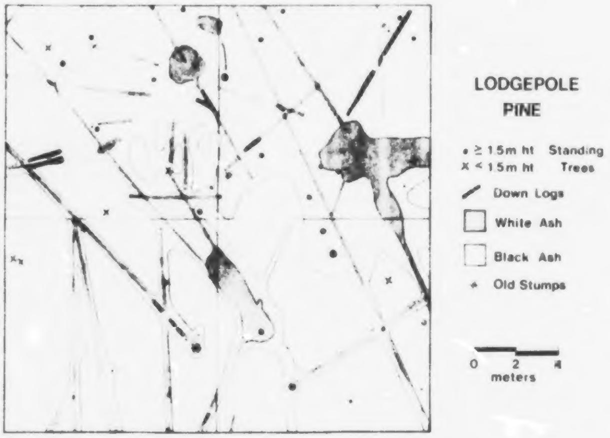

Figure 1. – Fire spread at the 1980 Sharp Peak fire in a climax lodgepole pine stand; fire smoldered along decayed logs with some litter consumption. The "white ash" areas were corridors along which logs were completely consumed, imposing a "pick-up sticks" matrix of fire spread across the landscape (from Agee 1981).

Fire Effects. – This unusual log-to-log smoldering pattern causes both above-ground and below-ground ecological effects. Above-ground effects include crown scorch and complete or partial girdling of the bole. In some cases, the below-ground impacts are even more significant. Where logs are consumed by fire, considerable heat is transferred into the soil (Figure 2), which may damage or kill the tops of tree roots that occur in these shallow-rooted forests (Hare 1961, Wright and Bailey 1982). Immediately after a fire many of the damaged trees are stressed and attacked by bark beetles. Accordingly, we chose three fire events (Bald Mt. 1982, Sharp Peak 1980, and Lookout Point 1898) to compare and develop a chronosequence of fire-wound initiation, scar formation and immediate post-fire scolytid activity.

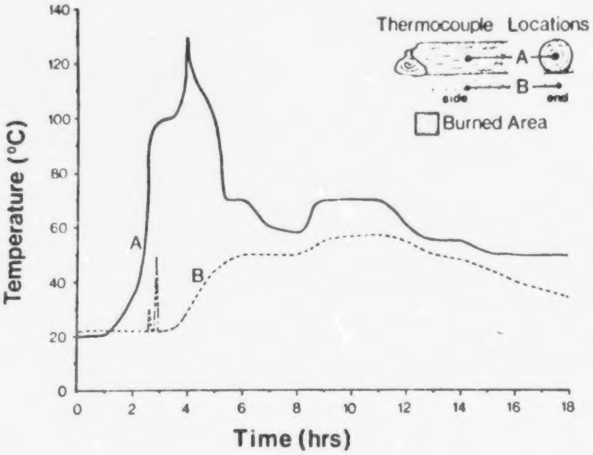

Figure 2. – Time temperature profiles recorded by a shielded thermocouple placed inside a smoldering lodgepole pine log (A) and one buried 5 cm below the log (B) at a 1980 Crater Lake NP fire.

After the Bald Mt. and Sharp Peak fires, surviving trees were classified into a series of bole damage types. Low basal wounds resulted from logs smoldering near a tree base; tapering basal wounds were caused by flaming logs; and ellipsoidal wounds, which did not have ground contact, were caused by radiant heat from flare-ups of fine fuels or intensely-burning logs. Typically, the amount of cambial circumference killed and associated root damage declined successively in tapering basal, low basal, and ellipsoid wound types. Furthermore, an additional 20% of the unwounded trees surveyed had at least one major lateral root killed by fire (Table 1).

In agreement with observations on other western conifers (Lachmund 1921), we found that charred bark covering dead tissues exfoliates within 3-5 yrs, thus exposing the wound surface and wound-callus tissue (scar formation). In subsequent decades, the exposed scars deteriorate by insect attack, fungal infection, and physical weathering; these scar faces then become surrounded by continual cambial growth. Using this sequence as a model, we matched a series of 85-yr-old scar types from the Lookout Point burn with corresponding wound types; an example of this morphological comparison is seen in Figure 3.

A year after the Bald Mt. fire and two years following the Sharp Peak fire, we established surveys to determine relationships between fire-damaged lodgepole pine and subsequent tree killings by *Ips pini* (Say) and *D. ponderosae.* Scolytid activity began within two weeks after the Sharp Peak and Bald Mt. fires and the proportion of infested trees increased with higher degrees of bole damage (Fig 4A). Furthermore, a higher proportion of undamaged and lightly damaged trees were attacked by *D. ponderosae* than the more severely fire-damaged trees, while *Ips* preferred the moderate to heavily fire-damaged trees (Fig. 4B). These scolytid attacks were correlated with percent bole damage, wound height, and percent root kill (Table 2). By using discriminant analysis methods, we showed that percent root kill was the most important fire-related variable associated with combined *Ips* and *Dendroctonus* attack. In addition to being correlated with degree of fire damage, *I. pini* attacks were negatively correlated with tree diameter, while *D. ponderosae* primarily attacked large diameter trees.

Table 1. – Fire damage observed on surviving lodgepole pines 2 years after the 1980 Sharp Peak burn. Results obtained from 10 (10 × 30m) plots established randomly throughout the burned area ± SE.

Wound Classification	$\bar{X}$ Diameter (cm)	% Tree Circumference Killed	% Trees with Damaged Roots
Tapered Basal n = 13	21 ± 2	51 ± 5	79
Basal n = 13	19 ± 3	39 ± 6	85
Ellipsoid n = 8	14 ± 2	19 ± 4	16
Unwounded n = 28	16 ± 2	–	18

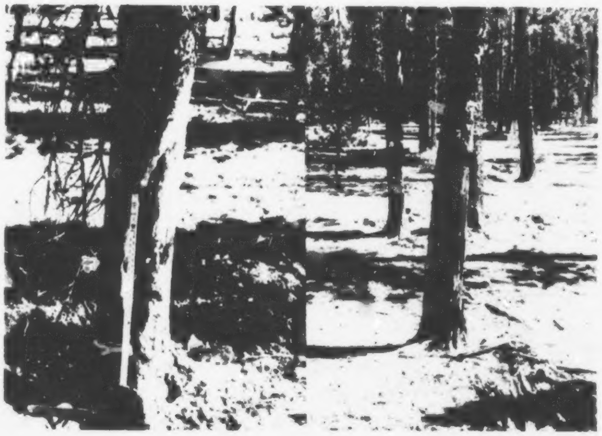

Figure 3. – Appearance of a tapering basal fire wound on a lodgepole pine after the 1980 Sharp Peak fire (left) as compared with a fire scar by an 1898 fire wound at Lookout Point (right).

Fungal Pathogens. – In order to link fires with establishment of fungal infection courts in the boles of trees (Geiszler *et al.*, 1980, Nordin 1958), we serially sectioned the boles and exposed the roots of about 100 trees that survived the various fires in our study area. We noted that within a year, newly fire-damaged root tissues were infected with fungi imperfecti and white-rot Basidiomycetes. In contrast, material from older fires yielded an abundance of brown-rot Basidiomycetes (Table 3).

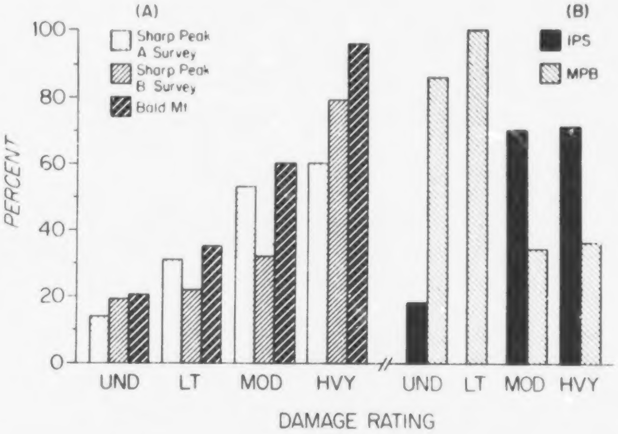

Figure 4. – (A) Percentage of lodgepole pine infested by scolytids as related to fire damage rating (undamaged, light, moderate and heavy); data recorded 2 years after the 1980 Sharp Peak fire (surveys A and B) and one year after the Bald Mt. fire. (B) Percent of trees infested by *Ips* and mountain pine beetles (MPB) as related to damage rating; data from Sharp Peak A survey (from Geiszler *et al.*, 1984).

Table 2. – Adjusted r^2 values from correlation analysis between the percent of trees attacked by scolytids per damage class and the percent fire damage, data from 1983 Bald Mt. survey.

Fire damage	Adjusted r^2 values	
	Ips	*MPB*
Wound height	.74	.79
Percent root kill	.74	.91
Percent bole kill	.96	.91

Fungal isolations made from tissues in the continuum between fire scars and the heart rot columns, of trees fire-scarred in 1898, yielded only fungi imperfecti and not wood-decaying Basidiomycetes. These fungi imperfecti were mostly *Leptographium* and *Paceliomyces* species associated with cerambycid and scolytid activity. In contrast the Basidiomycetes, *Poria asiatica, Gleophyllum odoratum, Lentinus lepideus, Pereniporia subacida* and *Tyromyces leucospongia* were consistently isolated only from decay columns. Among these later-occurring heart rot fungi, *P. asiatica* is ecologically most significant because it characteristically invades fire wounds and in doing so outcompetes contemporaneous white-rot species (Robinson-Jeffery and Loman 1963, Buckland 1946).

The presence of these two spatially distinct fungal floras together with the conical shape of the butt rot column strengthened the notion that these decay columns originated in fire-killed roots. Moreover, by tracing the development of fungal decay in fire-killed roots and subsequent decay spread into the stems of these trees, we substantiated the fact that fire-killed root tissues are the fungal entry courts and not above-ground bole damage (Fig. 5). For example, we found that 75% of trees at Lookout Point with fire scars also had fire-killed roots, as did 32% of the unscarred trees. In fact, there was a strong association ($\chi^2(1) = 16.5$, $P = .001$) between existing decay columns and the presence of fire-killed roots (Fig. 6).

Table 3. – Fungal isolates identified from lodgepole pines damaged during the 1980 Sharps Peak fire, 1976 Wickiup Springs fire and 1898 Lookout Point fire; isolations made from tissues associated with butt decay in fire-scarred (FS) trees, fire-killed (FK) roots, and down logs (DL), from Littke and Gara 1984.

Burn site	Years after fire	Fungal species	Rot[1]	%[2]	Material
Sharp Peak	2	*Pholiota carbonicola*	W	24	FK roots
		Trametes carbonaria	W	5	"
		Misc. fungi imperfecti etc.	–	71	
Wickiup	6	*Poria subacida*	W	25	FS trees/DL.
		Heterobasidion annosum	W	6	FS trees/DL.
		Lentinus lepideus	B	6	FK roots
		Sistotrema brinkmanni	B	6	FK roots
		Unid.	W	57	FS/FK trees
Lookout Point	84	*Poria asiatica*	B	13	FS trees
		Gloeophyllum odoratum	B	10	FS trees/DL.
		Lentinus lepideus	B	3	FS trees
		Tyromyces Leucospongia	B	8	DL.
		Poria taxicola	B	3	FS trees
		Poria subacida	W	3	DL.
		Coniophora sp.	B	5	DL.
		Unid. Basidiomycetes[3]	B	38	FS trees

[1] Rot type: W = white rot; B = brown rot.

[2] Percent total isolations per site, usually 8 isolations per specimen.

[3] Unidentified Basidiomycetes – usually isolated once, each species less than 1% of total isolates.

Within the first few years after a fire, the development of decay in trees may be largely controlled by the dynamics of fungal succession (Bourchier 1961). However, later, an increase in rate of decay development may relfect changes in host energy allocation patterns (Hoque 1982, Shortle 1979) (Fig. 7). In any case, ca. 5-6 decades after the Lookout Point 1898 fire, *P. asiatica* infected trees were growing significantly slower ($P = 0.05$) than uninfected neighboring trees of equal diameter and age class (Fig. 8). The existence of a stand comprised of a mosaic of infected and uninfected trees will have important consequences with regard to mountain pine beetle population dynamics.

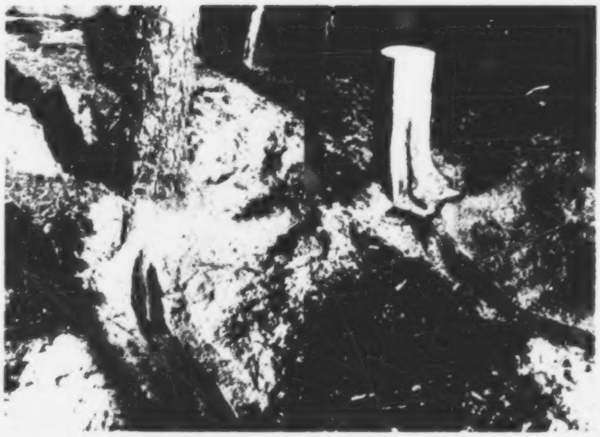

Figure 5. – A 140-yr-old, unscarred lodgepole pine growing in the 1898 Lookout Point fire site with fire-scarred root (left). A crossection of the bole showing decay column associated with the fire-damaged root (right).

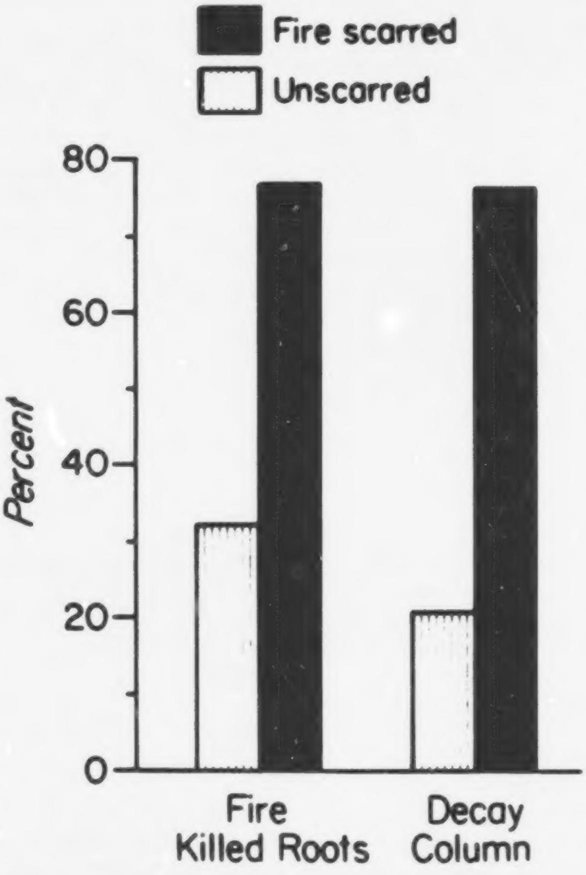

Figure 6. – The percentage of fire-scarred and unscarred lodgepole pines with fire-killed roots (left), and those with active decay columns (right); data from 44 trees sampled at the 1898 Lookout Point fire (from Littke and Gara 1984).

Host Selection Patterns. – During the first few years of an outbreak more fire-scarred than unscarred trees are killed by *D. ponderosae*, and, moreover, fire-scarred trees have more advanced decay and fungal stain than unscarred trees (Geiszler *et al.*, 1980). An important remaining question is whether or not dispersing beetles preferentially land on fungal infected trees.

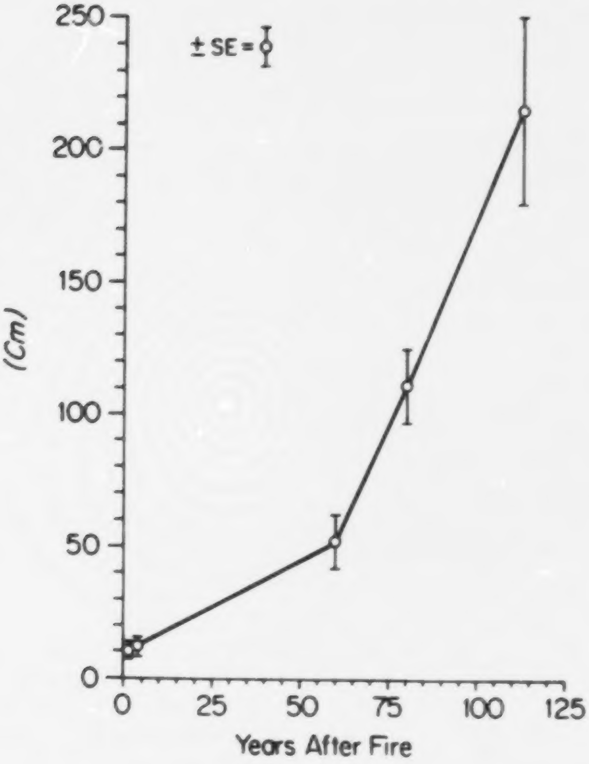

Figure 7. Vertical development over time of active decay columns in lodgepole pine whose lateral roots were damaged by fires in 1870, 1898, 1920, 1976, or 1980 respectively (from Littke and Gara 1984).

We investigated this question by establishing modified window traps (Chapman and Kinghorn 1955) on *P. asiatica* infected and uninfected trees. These tests were done at a time before trees throughout the Lookout Point area were being attacked. These studies (Fig. 9) indicated that dispersing beetles preferentially landed on fire-scarred trees (P = .03) and particularly on trees with fungal decay (= .003) (Gara *et al.*, 1984). These results confirm the existence of preferred focus trees – trees initially selected by dispersing beetles at a time before the population is concentrating.

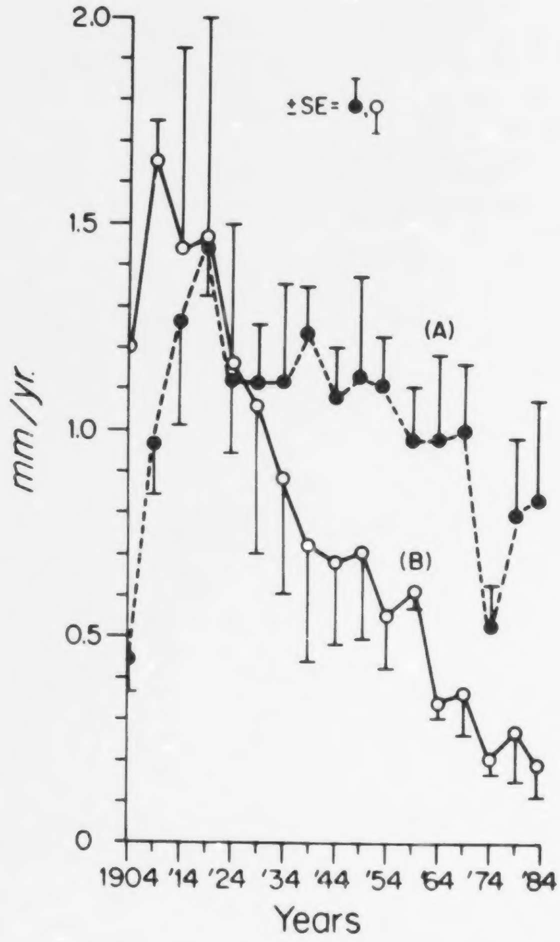

Figure 8. – Mean annual increment ($mm \cdot yr^{-1}$) of adjacent pairs of similar diameter lodgepole pines following the 1898 Lookout Point fire. One member of each pair was undecayed and unscarred (A); the other member was fire-scarred and had an active decay column (B) (Littke and Gara 1984).

To simulate the concentration phase of the *D. ponderosae* host selection pattern, we placed window traps and synthetic pheromones on selected hosts (focus trees). Trees over 20 cm dbh that surrounded these baited trees (recipient trees) also were supplied with window traps. The synthetic pheromone was removed when at least 10 attacks occurred on the baited trees; further attacks on these trees augmented naturally. Attacks were tallied hourly within a 2-m band, 1.2 m above the ground. Similarly, window traps were emptied and beetles recorded every hour. The sequential progression of attacks and landings on bait trees and adjacent trees was followed for several days.

The rate of beetle landings on the bait tree was synchronous with the attack pattern. When the attack rate on the baited trees leveled off, presumably in response to antiaggregants, a few beetles landed on a neighboring tree. Almost immediately these recipient trees in turn were mass attacked (Fig. 10).

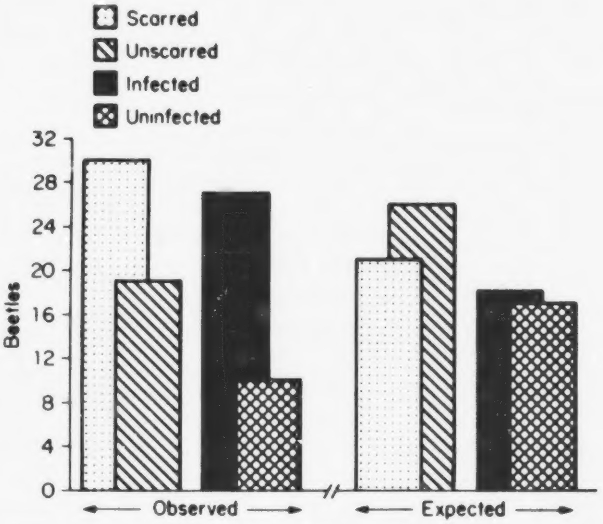

Figure 9. – Observed number of *D. ponderosae* landings and expected number of landings (assuming random selection) on fire-scarred and unscarred as well as fungus-infected and uninfected lodgepole pine at Lookout Point (see appendix).

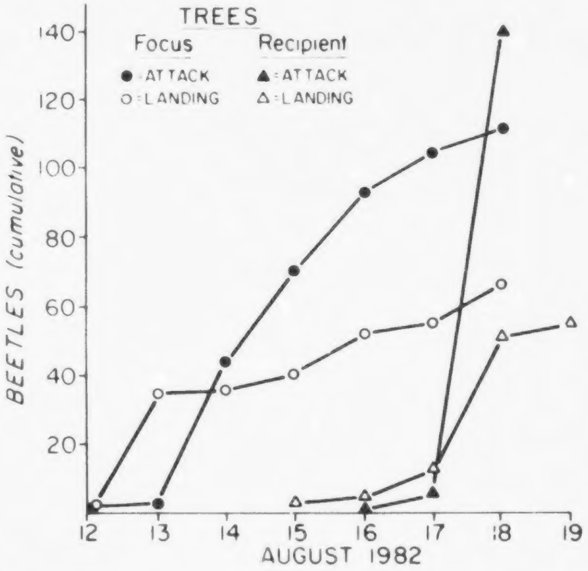

Figure 10. – Cumulative numbers of *D. ponderosae* landings and attacks on lodgepole pines initially baited with synthetic pheromones (focus trees) and later on adjacent stems (recipient trees); studies conducted at Lookout Point area.

These observations demonstrate that once a focus tree is selected and attacked, recipient trees are precipitously attacked by interactions between pheromones; moreover, diameters and distance of adjacent stems play important roles in this serial attack pattern – the switching mechanism described by Geiszler and Gara (1978). Thus the potential for *D. ponderosae* outbreaks increases proportionately with the abundance of focus trees and the spatial distribution of suitable neighboring hosts (Amman and Cole 1983).

Stand Structure. – Lodgepole pine reproduction of our study areas occurs when root competition between trees is drastically reduced: a situation following mountain pine beetle outbreaks and fire events. This seedling establishment pattern was due to increased moisture availability in the vicinity of recently-killed tree clumps and a relatively favorable microclimate provided by logs and standing dead trees – both of which favor seedling establishment (Stuart 1983). We therefore attempted to link current stand structure with previous fires and *D. ponderosae* disturbances. Accordingly, we established plots in areas of widely divergent fire histories and collected dendrochronological data associated with fire scars, *D. ponderosae* outbreak history (for methods see Stuart *et al.*, [1982], Mitchell *et al.*, [1982]) and subsequent regeneration patterns.

While suitable hosts were randomly spaced, beetle-killed trees were usually found in statistically-clumped patterns (Stuart 1983), a finding in support of the switching mechanism (Geiszler and Gara 1978). Therefore, seedling establishment should be closely associated with these clumps of beetle-killed trees. This was tested by mapping seedling groups and groups of recently killed trees. Seedling groups were defined by the presence of beetle-killed trees and their zone of competitive influence (half the distance between a beetle-killed tree and the nearest live tree). Maps of both of these groups were superimposed on one another. A variety of statistical tests of association, including the chi-square test of independence, showed that there was statistical association of seedling groups with groups of beetle-killed trees (Stuart 1983). Therefore, regeneration patterns would be closely associated with these clumps of beetle-killed trees. Since beetle outbreaks historically continue for several years, regeneration establishment would temporally follow these outbreak periods.

Similarly, fires also are important in creating growing space for seedling regeneration. Depending on fire behavior, individual trees to entire stands may be killed; and this is reflected in subsequent regeneration patterns. A single light ground fire (Agee 1981) would maintain a predominance of two age classes. As a consequence of fuel patterns, stands that develop after these light fires tend to be a mosaic of surviving older residual trees and younger regeneration that occurs either randomly or in discrete patches. An intense fire would create conditions for a single age-class stand to develop.

A series of line transects within the Lookout Point area were used to describe regeneration patterns associated with past fire and mountain pine beetle activity. These transects crossed four distinct areas defined by community structure and fire history:

(1) a ridgetop ponderosa pine community characterized by a varied fire history; (2) an ecotonal zone between the ponderosa pine ridgetop and the climax lodgepole situated in the flats below; (3) the climax lodgepole pine flats, which experienced an 1839 stand regeneration fire and an 1898 light ground fire; and (4) an adjacent climax lodgepole pine area that had not had a fire for at least 350 years.

Based on the distribution and ages of single and multiple fire scars, we found that, historically, fires originated in the ponderosa pine ridgetop and ecotonal zone and moved into the climax lodgepole pine flats in accordance with the smoldering log fire model. Regeneration patterns of the ridgetop and ecotonal areas were heterogenous, reflecting the seedling establishment after a series of fires that spanned the last three centuries. In contrast, regeneration patterns of the lodgepole pine flats, which experienced only two fires, were bimodal–trees initiated in 1840 and 1899. The climax lodgepole pine stand that had no fires in the last 350 years had a variety of age classes (85 to 350 yrs) that occurred in clumps. Since fire scars were absent in this stand, we feel that this clumped regeneration pattern resulted from sporadic removal of trees by *D. ponderosae.*

Synthesis. – We propose the following conceptual model that integrates the effects of fire, fungi and mountain pine beetles in development of lodgepole pine stands in the Lookout Point area (Fig. 11). During 1839, fuel conditions and weather were ideal for spread of a stand replacement fire throughout a large portion of the Lookout Point area. This fire eliminated root

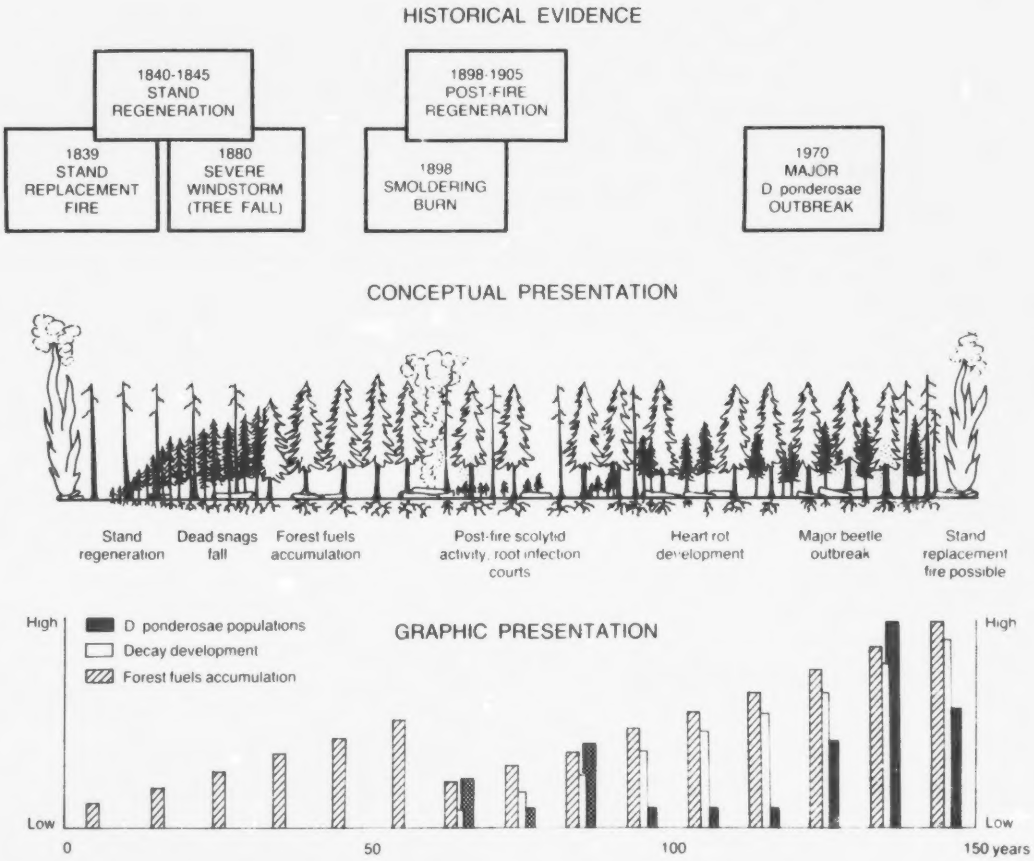
HISTORICAL EVIDENCE
1840-1845 STAND REGENERATION
1839 STAND REPLACEMENT FIRE
1880 SEVERE WINDSTORM (TREE FALL)
1898-1905 POST-FIRE REGENERATION
1898 SMOLDERING BURN
1970 MAJOR D ponderosae OUTBREAK
CONCEPTUAL PRESENTATION
Stand regeneration
Dead snags fall
Forest fuels accumulation
Post-fire scolytid activity, root infection courts
Heart rot development
Major beetle outbreak
Stand replacement fire possible
GRAPHIC PRESENTATION
D ponderosae populations
Decay development
Forest fuels accumulation
High
Low
High
Low
0
50
100
150 years

Figure 11. – Interactions between fires, fungi, and mountain pine beetles observed at Lookout Point – a climax lodgepole pine forest of the Oregon pumice plateau.

competition between trees and a new lodgepole pine stand was established. As this fast growing new stand emerged, there developed a strong competition for light and moisture, resulting in mortality of suppressed trees. Over the next 60 years, these small dead trees provided low-decay type fuels that laid on top of more decayed logs that were remnants of the 1839 fire.

In 1898 the fuel bed was optimal for spread of a slow-moving fire, similar to that described by Agee (1981) at Sharp Peak and noted in the 1982 Bald Mountain fire. This is the type of fire that not only further thinned the stand (i.e., through outright killing of trees and subsequent scolytid attack), established reproduction patches, but also wounded major lateral roots and boles of many of the residual trees. This root wounding provided infection courts for invading white rot fungi. Afterwards, a succession of fungi conditioned the root tissues for infection by the brown rot complex with *P. asiatica* being one of the principal agents. In time, the impact of this fungal action essentially created trees that were susceptible to attack by dispersing mountain pine beetles (focus trees).

During development of the beetle outbreak at Lookout Point, the beetles preferentially attacked the largest diameter trees with advanced butt rot. In subsequent years the largest of the remaining trees were killed until the remaining stems were too small to support beetle populations (also see Cole and Amman 1980).

A different set of fire-fungi-*D. ponderosae* interactions occurred in the fourth transect area, which did not experience either the 1839 or 1898 fires (Table 4). While the Lookout Point area underwent a recent mountain pine beetle outbreak, the "no fire" area has had no outbreak. Fungal-infected trees over 200 years old were being killed either singly or in small groups by beetles, and tree regeneration was establishing in the same pattern. The more diverse structure of this stand has apparently conditioned it to experience frequent but minor beetle disturbances, in contrast to the more wave-related fire, fungi, and beetle disturbances at Lookout Point.

Table 4. – A comparison of lodgepole pine stands of the "no-fire area" with those of the climax lodgepole pine flats of the Lookout Point site.

Characteristics	"No-Fire Area"	Lookout Point
D. ponderosae status	single or small group kills	recent massive outbreak
Potential focus trees	scattered	predictable and generally the large diameter fire-scarred trees
Fire scars	none	plentiful as over 50% of the stems scarred by the 1898 fire
Fungal status	variable and mainly found in trees selected by *D. ponderosae*	fire-scarred dominants with advanced *P. asiatica* infection
Age structure	tree patches of variable ages with 200-yr-old dominants	dominants predominately 142 years old with scattered 84-yr-old reproduction patches

CONCLUSIONS

Our current research provides evidence that the actions of fire, fungi and mountain pine beetle attacks are all tightly woven together in an ecosystem that perpetuates lodgepole pine in the tephra-derived soils of south central Oregon. All other stand factors being equal (stocking, competition, nutrients and so forth), the spatial arrangement of decayed trees (focus trees) and adjacent trees of suitable size in the stand ultimately dictates the magnitude of *D. ponderosae* outbreak.

Understanding the interactions of fire, fungi, and mountain pine beetle populations are advantages forest managers would have in their attempt to minimize the effects of scolytid epidemics. In particular, understanding the dynamics of lodgepole pine stands would make it possible for managers to project ahead to the optimum time to harvest trees, conduct prescribed burns, or artificially intervene in the normal dynamics of the forest ecosystem.

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APPENDIX

As the number of test trees "available for landing" changed during the study (Fig. 9) we used the joint binomial distribution to compute the probabilities of a *D. ponderosae* landing on a fire-scarred tree – we term this type of landing a "success." The joint binomial distribution takes into consideration that the probability of a success can be different for changing (or different) sample sets. This distribution can be described as

$$P(S<s) = \Sigma \prod_{i=1}^{K} \binom{N_i}{M} \; p^{M_i} (1-p_i)^{N_i - M_i}$$

where S is a random variable for the number of successes, s is the observed number of successes, K is the number of sample sets taken, N_i is the number of samples in the i^{th} set, m_i is the observed number of successes in the i^{th} set, and p_i is the probability of a success in the i^{th} set. The summation (Σ) is taken over all values of M_i such that $S = \sum_{i=1}^{K} M_i$ is greater than $s = \sum_{i=1} m_i$ and $) \leq M_1 \leq N_i$ (from Gara *et al.*, 1984).

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ASSESSING THE RISK OF LODGEPOLE PINE STAND DESTRUCTION BY PESTS

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ABSTRACT

Destructive outbreaks of forest pests are classified as gradient, cyclical or eruptive. The first two types of outbreaks (gradient, cyclical) are generated by stand and site conditions conducive to the reproduction and survival of the pest or stressful for the host plant(s). In these cases, outbreak probability, or risk, can be assessed with unidimensional risk equations. Outbreaks of the third type, the eruptive pests, are more difficult to predict because the density of the pest plays a critical role in initiating outbreaks in particular stands. Risk assessment models for these pests require a two-dimensional structure that integrates stand, site and insect numbers. We discuss methods for developing risk assessment models for eruptive pests using, as an example, mountain pine beetle populations infesting lodgepole pine stands.

INTRODUCTION

Risk assessment has long been the key to successful fire management and entomologists have attempted to develop similar risk assessment methods for forest insect pests. Insects and other pest organisms (pathogens, ungulates, rodents, porcupines, etc.), however, have complex biologies and behaviors and their populations are affected by a large number of variables. These complicating factors make it more difficult to develop accurate methods for assessing the risk of destructive pest outbreaks.

Risk assessment models for forest insects have traditionally been constructed from empirical observations on the association between insect damage and various site and stand conditions, or on the vigor status of individual trees (see Hedden *et al.*, [1981] for a number of examples). These models may be purely qualitative (e.g. Amman *et al.*, 1977) or may utilize statistical analyses such as regression or discriminant analysis to formulate predictive equations (e.g. Schenk *et al.*, 1976; Kushmaul *et al.*, 1979; Stoszek *et al.*, 1981; and papers in Hedden *et al.*, 1981). However, most of these models suffer from two fundamental flaws: (1) they are sometimes constructed without the basic principles of population dynamics in mind, and (2) being purely empirical, they often fail when predictions are extrapolated beyond the range of the data on which the model was built. In the present paper, we develop a general framework for constructing risk assessment models for pest organisms based on the principles of pest population dynamics. We then show how empirical data can be used to provide the flesh for this skeletal framework. We believe that models of this type will have wider applications and will provide more insight into alternative ways to combat pests.

WHAT IS RISK ASSESSMENT?

The literature on risk assessment is somewhat confused, with terms such as risk, hazard, and vulnerability sometimes being used interchangeably. We restrict our usage of risk to: *the likelihood, or probability, of a damaging event occurring within a specified time frame and under a given set of conditions.* In this way risk has a common meaning in all walks of life; the risk of an automobile accident, contracting a disease, being robbed, or suffering an insect outbreak or fire on your district. This concept of risk, therefore, does not concern itself with the *extent* of damage (the cost of repairs to your automobile or the value of timber killed) but purely with the event itself. The risk of a pest outbreak, therefore, is specified as a probability $P\{0\}$, while damage is predicted under the assumption that the outbreak will occur, or is measured after the fact (i.e., $P\{0\} = 1$).

Like any insurance company, forest managers would like to find associations between risks and measurable variables. If this is possible, then risks can be minimized by controlling the critical conditions, e.g., cigarette smoking, fast driving or unhealthy stands. *Risk assessment,* therefore, involves the twin activities of *understanding the causes* of the damaging event and formulating a *predictive model* based on this understanding.

THE CAUSES OF PEST OUTBREAKS

In the last half century a great deal of information has accumulated on the population ecology of pest organisms, particularly insects. From these studies have come the general conclusion that pest outbreaks usually exhibit one of three basic patterns:

1. *Pest gradients:* Some species exhibit characteristic levels of abundance that are completely determined by some critical environmental factor (Fig. 1). For example, fir engraver beetle populations are determined by the abundance of susceptible firs in the stand. When large numbers of host trees are weakened by drought, competition, or defoliation by Douglas-fir tussock moths, the engraver population explodes, but returns to normal endemic levels as soon as the trees recover (Site C in Fig. 1 upper) (Berryman, 1973; Schenk *et al.*, 1976). Populations of the Douglas-fir beetle (Furniss, 1981) and some tip moths (Stoszek, 1973; Heikkenen, 1981) also seem to fit this pattern. Because the behavior of these insect pest populations is a graded response to certain critical environmental variables, we use the term *gradient* to describe their behavior.

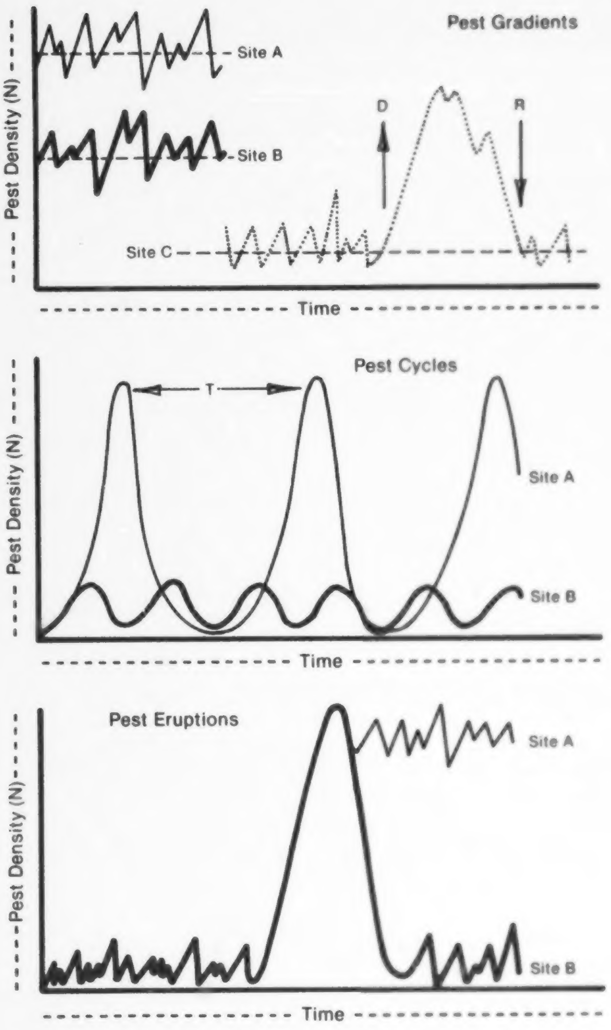

Figure 1. The three major patterns of pest population dynamics:
Gradients—Pest average density is determined entirely by conditions on the site (soil, topography, stand structure and composition, etc.) and by environmental factors that disturb site or stand conditions (drought, windstorms, etc.). A spatial gradient exists between sites A, B, and C and, in addition, a temporal gradient occurred on site C when a disturbance D caused the pest population to increase until site conditions returned to normal, R.
Cycles—Pest density is dependent on intrinsic cyclicity with predictable periodicity, T, but peak densities are determined by conditions on the site.
Eruptions—Pest density remains very low for long periods of time but eruptions to very high densities occur at irregular intervals. High population densities may persist (A) or collapse back to endemic levels (B). Outbreaks are triggered by conditions on the site and/or environmental disturbances.

2. *Pest Cycles:* The second group of pest organisms exhibit regular, and often predictable, cycles of abundance, and are thus classified as *cyclical* pests (Fig. 1, middle). Some well documented examples are the Douglas-fir tussock moth in western North America (Brookes *et al.*, 1978), the larch budmoth in Switzerland (Baltensweiler, 1977), and the autumnal moth in Scandinavia (Haukioja, 1980). The exact causes of Douglas-fir tussock moth population cycles are unknown, but in the two European species cycles appear to be the result of interactions with the host plant (Benz, 1974; Haukioja, 1980). In all species, however, the amplitude of the cycles, and hence the severity of the outbreak, seems to be associated with site and/or stand factors. For instance, the intensity of Douglas-fir tussock moth outbreaks is associated with the aspect, elevation, and soil structure of the site, and with stand density and structure (Stoszek *et al.*, 1981). Thus, outbreaks of cyclic pests are often dependent on site and/or stand conditions but also, in a fairly predictable manner, on the time since the last outbreak (Fig. 1, middle).

3. *Eruptive Pests:* The last group of pests are termed *eruptive* because they remain at very low densities for long periods of time but then suddenly explode to very high epidemic levels (Fig. 1, lower). These high densities may be sustained for a period of time (Fig. 1A) or may quickly subside to the endemic level (Fig. 1B). Examples of eruptive pests are the mountain pine beetle (Berryman, 1982), the eastern spruce budworm (Morris, 1963), and the gypsy moth (Campbell and Sloan, 1978). During their extended endemic period, these pests are regulated by a scarcity of susceptible host material (mountain pine beetle) or by their natural enemies (vertebrate predators in the eastern spruce budworm and gypsy moth). Eruptive outbreaks are usually initiated at irregular intervals when the regulating factors are no longer able to maintain control of the pest populations. Moreover, once the outbreak has started in a particular stand, it usually spreads to adjacent stands as migrating pests overwhelm the controlling influence of the regulating factors. For instance, large numbers of migrating mountain pine beetles can overwhelm the defenses of even healthy lodgepole pines (Raffa and Berryman, 1983) and gypsy moths can saturate the feeding responses of their vertebrate predators (Campbell and Sloan, 1977). In these types of pests, therefore, the likelihood of an outbreak in a particular stand is affected by pest population density as well as site and stand conditions.

GENERALIZED RISK MODELS

There are three basic requirements for a *practical* risk assessment model:

1. A device for predicting the probability of a pest outbreak under a variety of site and/or stand conditions. This device may be a mathematical equation, a graph, or a set of simple decision rules. From the standpoint of practicality, equations should be easily solved by hand, or, at most, with pocket calculators.

2. The variables used in constructing the risk model should be easily measured by standard mensurational techniques and

should be amenable to manipulation by standard management practices (e.g. planting, harvesting, thinning, etc.).

3. The model chosen should be appropriate for the pest species in question and should consider the kind of population pattern exhibited by the pest.

Risk assessment models attempt to associate a *dependent variable,* the probability of an outbreak, with a set of *independent variables* which can be measured in the field. The independent variables are usually of two types: *Spatial predictors* that predict *where* an outbreak is likely to occur, and *temporal predictors* that forecast *when* the outbreak is likely to occur. Spatial predictors are usually site or stand variables such as site xericity (dryness), topography, soil structure and stand density, age and species mix (Table 1). These variables change rather slowly, and, therefore, provide the manager with time to plan and execute silvicultural treatments. They also provide the silviculturist with practial guidelines: e.g., planting trees on low-risk sites, thinning dense high-risk stands, changing species mix to lower risk, etc.

Temporal predictor variables usually change rapidly and act as disturbances to site and stand conditions. Climatic variations (particularly precipitation), biotic variables (root pathogens and insects) and man-induced disturbances (logging, construction) can all act to upset normal site and stand conditions (Table 1).

In the present paper we develop risk assessment models around spatial predictors because they provide the manager with practical silvicultural solutions. Temporal predictors will either be considered as random variables or as flags or *warnings*, alerting the manager to the fact that the basic risk assessments may require adjustment.

Table 1.—Some site, stand, and disturbance variables that have been associated with the levels of abundance of various insect pests

Insect/Host	Population Type	Predictor Variables		
		Site	Stand	Disturbance
Fir engraver/ grand fir[1]	Gradient	Xericity	Density Species mix	Drought Pathogens Defoliation Logging
Balsam woolly aphid/true firs[2]	Gradient?	Elevation Xericity	Density Species mix	
Douglas-fir Tussock moth/ grand fir[3]	Cyclic	Slope Aspect Elevation Ash depth	Age Density Species mix Crown structure	
Eastern spruce budworm/balsam fir[4]	Eruptive		Age Density Species mix	Climate
Mountain pine beetle/lodgepole pine[5]	Eruptive	Elevation Aspect	Age Diameter Density Species mix Growth rate Vigor	Drought Lightning

References

[1] Schenk *et al.*, (1976); Berryman (1973); Hertert *et al.*, (1975).

[2] Page (1975).

[3] Heller and Sader (1980); Stoszek *et al.*, (1981).

[4] Morris and Bishop (1951); Blais and Archambault (1982).

[5] Safranyik *et al.*, (1974); Amman *et al.*, (1977); Berryman (1976); Mahoney (1978); Schenk *et al.*, (1980); Mitchell *et al.*, (1983).

Models for Gradient Pests

Because the average density of gradient pests changes as a continuous function of certain site and stand variables, a decision has to be made as to what level of pest density constitutes an outbreak. This can only be done with the assistance of the forest manager and his planning staff. From the management standpoint, an outbreak occurs when the damage caused by an insect population reaches a level where serious economic losses are incurred (losses may be due to mortality, growth loss, deformity, delayed regeneration, harvesting costs, lowered grade, etc.). This critical damage level is often called the *economic damage threshold*. If this threshold can be defined, then a risk model can be developed from post-mortem studies in which a large number of stands are selected based on differing levels of damage. These stands are then classified, on the basis of the economic damage threshold, into outbreak and non-outbreak stands. They are then entered and measurements taken of as many site and stand variables as possible. The data are then subjected to analysis to screen out the insignificant predictor variables (e.g., Hamilton and Wendt, 1975) and then an outbreak probability model is constructed by fitting the signficant predictors to an appropriate equation, such as the "logistic" model (Hamiton, 1974; Stage and Hamilton, 1981). The fitted model can then be used directly to compute outbreak probabilities for particular stands by measuring the predictor variables and solving the equation on a programmable pocket calculator.

Risk assessment models for pests that exhibit gradient population patterns, will have the general form

$$P\{o\} = f(SI, ST) \pm e \qquad \text{(Eq. 1)}$$

where the probability of outbreak, $P\{0\}$, is expressed as a function, f, of a set of site, SI, and stand, ST, predictor variables. The error term e is composed of random experimental errors and time-dependent disturbance variables. When information is available on the disturbing factors they can be used to modify the model predictions or as warning flags.

Models for Cyclic Pests

In general, risk models for cyclic pests will be similar to those for the gradient type. This is because peak population densities are usually associated with site and/or stand conditions (Fig. 1 and Table 1). Thus, the analytical methods suggested above are also appropriate for cyclic pests. Data for fitting the model (Eq. 1), however, should only be collected during years of peak abundance.

With cyclic pests we also have a strong temporal predictor available because the period between peak densities is relatively constant. If the question, "when will an outbreak occur?" is deemed important we can formulate the model as

$$P\{0\} = f(SI, ST, T) \pm e \qquad \text{(Eq. 2)}$$

where T is the time since the previous outbreak. Climatic and other disturbances are still incorporated into the error term and may act to amplify or suppress the height of the cycles.

Models for Eruptive Pests

Like the other two pest types, eruptive outbreaks are also associated with particular site and/or stand conditions (Table 1). Unlike them, however, they are critically dependent on two counteracting pressures: those that generate more pests, and those that restrict pest numbers. Of course, all pest populations are affected by these pressures but, in the case of eruptive pests, the restrictive forces become less effective as the pest population rises. For example, the defense systems of healthy lodgepole pines can prevent small mountain pine beetle populations from attacking successfullly but may be ineffective against large populations (Berryman, 1982; Raffa and Berryman, 1983). Similarly, vertebrate predators may be capable of regulating sparse gypsy moth populations but become ineffective when these populations are large (Campbell and Sloan, 1977).

For eruptive pests, therefore, risk equations will be two-dimensional, one function equating pest numbers, N, to a set of measurable site and/or stand variables, and the second function specifying the threshold pest population density required to saturate the suppressive forces, N_t, in relation to another set of site and stand variables. Hence,

$$N = f_1(SI, ST) \pm e_1 \qquad \text{(Eq. 3a)}$$

$$N_t = f_2(SI, ST) \pm e_2 \qquad \text{(Eq. 3b)}$$

The probability of an outbreak occurring is then a function of the difference between the potential pest population N and the threshold density N_t; i.e.,

$$P\{0\} = f_3(N - N_t) \pm e \qquad \text{(Eq. 4a)}$$

$$P\{0\} = f_3(f_1[SI, ST] \pm e_1 - f_2[SI, ST] \pm e_2) \qquad \text{(Eq. 4b)}$$

Defining such complicated functions poses severe analytical problems and, even if the relationships can be defined, computational difficulties will usually limit application under field conditions.

An alternative graphical method has been proposed for assessing the risk of eruptive pest outbreaks (Berryman, 1978, 1980, 1982). We will examine thie approach below with particular reference to the mountain pine beetle infesting lodgepole pine stands.

ASSESSING THE RISKS OF MOUNTAIN PINE BEETLE OUTBREAKS

A number of methods have been proposed for assessing the risk of mountain pine beetle outbreaks (Amman *et al.*, 1977;

Schenk *et al.*, 1980; Berryman, 1978; Mahoney, 1978). The models of Amman *et al.*, (1977) and Schenk *et al.*, (1980) assume that risk (or damage) is related to site or stand variables unidimensionally (i.e., in a similar manner to Eqs. 1 and 2). The model proposed by Berryman (1978) and applied by Mahoney (1978) assumes a two-dimensional structure (i.e., Eq. 3) and, therefore, seems more appropriate for an eruptive pest such as the mountain pine beetle. We will examine this model below.

The first problem is to derive a function relating pre-outbreak beetle densities per hectare to site and/or stand variables (Eq. 3a). The literature generally supports the assumption that pre-outbreak population levels are determined by the number of severely weakened trees in the stand (mainly lightning-struck trees) and the thickness of the phloem tissue of infested trees (Amman, 1972; Berryman, 1976). Of these two variables, only phloem thickness can be easily measured, or estimated from tree diameters (Cole, 1973). As the probability of a tree being struck by lightning and having phloem thick enough to generate more beetles than it absorbs (phloem >0.25 cm), is proportional to the percentage of these trees in the stand, we used the percent of the stand basal area with phloem greater than 1/4 cm thick (PHL) as the predictor variable. Hence,

$$N = f_1(\mathrm{PHL}) \pm e_1 \qquad \text{(Eq. 5a)}$$

where e_1 reflects the random variation, such as lightning strikes and measurement errors.

The next step is to define the relationship between the outbreak threshold, N_t, and site and/or stand variables. Experimental studies by Waring and Pitman (1980) and Raffa and Berryman (1983) demonstrate that the threshold beetle density required to kill normally healthy lodgepole pines is directly related to the resistance (defensive vigor) of the attacked trees. Pine resistance to attack, on the other hand, seems to be associated with growth efficiency (Waring and Pitman, 1980; Mitchell *et al.*, 1983) or periodic growth rates (Mahoney, 1978; Raffa and Berryman, 1982), as well as crown competition and species mix (Schenk *et al.*, 1980) and tree age (Safranyik *et al.*, 1974). Mahoney (1978) chose to express stand resistance in terms of three variables: periodic growth ratio, PGR; stand hazard rating, SHR, which is a complex variable composed of the stand crown competition factor and lodgepole pine species composition; and average stand age, AGE. Hence, from eq. 3b we have

$$N_t = f_2(\mathrm{PGR, SHR, AGE}) \pm e_2 \qquad \text{(Eq. 5b)}$$

where e_2 may contain random climatic variations (droughts may be particularly important) as well as measurement errors.

Having decided on the predictor variables, the next problem is to determine the threshold function (Eq. 5b). This is no easy task because thresholds are transient states that cannot be directly observed; i.e., the threshold is the beetle population density required to invade a stand of given resistance. We can, however, approximate the threshold function by indirect methods.

We first have to find a group of stands that are in the early stages of an outbreak (epidemic stands) but are not too close to an outbreak area (remember that migrating beetles can raise N and trigger an outbreak). Another set of stands must then be selected that do not appear to be undergoing an outbreak (endemic stands). These stands are then entered and the predictor variables are measured (e.g. PHL, PGR, SHR, AGE). Over the next 5 years or so, beetle-caused mortality must be measured to confirm the endemic-epidemic dichotomy. After the status of each stand has been adjusted by these observations the data are plotted as a two-dimensional graph (Fig. 2). The outbreak threshold is then drawn as a line which most clearly segregates epidemic from endemic stands. Note that because endemic stands can become epidemic due to beetle immigrations or disturbances (e.g., epidemic stands 9 and 10 in Fig. 2), the threshold need not exclude all epidemic stands. However, endemic stands must fall to the right of the threshold.

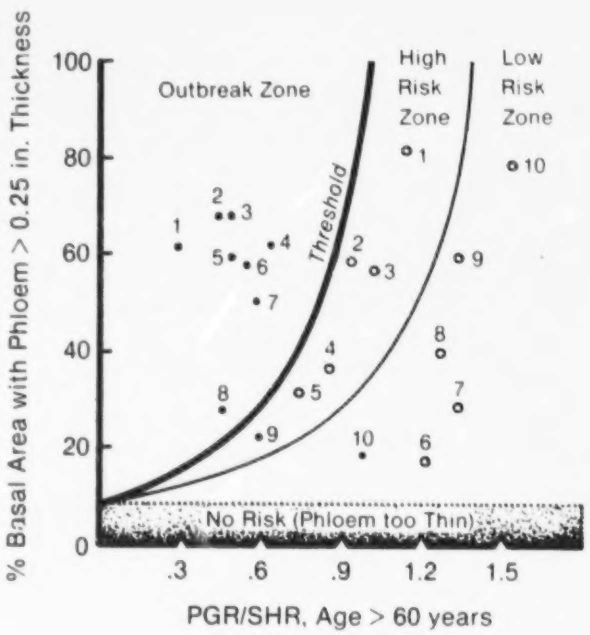

Figure 2. – Determination of the approximate outbreak threshold for the mountain pine beetle in lodgepole pine stands and assignment of risk zones. ● = outbreak stands, o = endemic stands; PGR = current 5 year growth increment/previous 5 year growth increment; SHR = crown competition factor × proportion of basal area in lodgepole pine (after Mahoney [1978] and Berryman [1978]).

Having found the approximate location of the outbreak threshold we can now formulate a risk model. Obviously, stands in the outbreak zone must have an outbreak probability of unity (i.e., P{0} = 1). It is equally evident that endemic stands close to the threshold (e.g., endemic stand 2) will have a high probability of entering the outbreak zone when disturbed by drought, lightning storms, etc. Stands remote from the threshold (endemic stand 10), however, are much less likely to be pushed over the threshold by disturbing variables (small disturbances are more likely than large ones!). On this basis risk zones can be assigned to the model (Fig. 2) with the width of the zones reflecting the risk-aversion of the forest manager.

Risk models of this type provide an effective means for planning and evaluating pest management options. For example, they can be applied by silviculturists when developing stand prescriptions. All that is required is a random sample of 100 trees or so from which phloem thickness (bark punch), periodic growth ratio and age (increment core), crown competition factor (estimated from basal area), and proportion of lodgepole pine basal area are measured. The location of the stand is then plotted on the risk graph (Fig. 2). Silvicultural prescriptions can then be based on the likelihood of stand destruction by the mountain pine beetle.

The model can also be used by forest planners in conjunction with a stand growth model such as the USDA Stand Prognosis Model (Stage, 1973). Stand trajectories plotted on the risk graph can be used to evaluate the likelihood of beetle epidemics during different phases of stand development (see Berryman, 1978, 1982). Harvesting plans can then be based on these risk projections.

Lastly, the model can be used for testing various intermediate stand treatments. For example, the effects of various thinning treatments can be evaluated by simulation on a stand growth model and displayed as a stand trajectory on the risk graph.

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REGENERATION

ADVANCES IN LODGEPOLE PINE REGENERATION

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and
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ABSTRACT

Successful regeneration of lodgepole pine is still an art, but the attainment of target stands with sufficient numbers of healthy, well-distributed seedlings has been made more attainable by scientific and operational advances since the 1973 symposium.

Clearcutting is still the predominant method used to regenerate stands of lodgepole pine, and partial cutting practices are restricted to use in special situations, particularly in the southern part of the natural range. In all areas successful natural regeneration depends upon the manipulation of seed supply and exposure of mineral soil. Methods for estimating seed supplies, and improvements in site preparation techniques, have increased the ability of silviculturists to achieve an optimum combination of seed supply and seedbed over a wide range of sites. Excessive stocking is a larger problem than inadequate stocking in Canada.

Artificial regeneration by means of direct seeding is used very little, but new spot seeding techniques coupled with seed protection from rodents could lead to a resurgence of interest because of the relatively high costs of planting.

Planting efforts have increased substantially as a means of both replacing pine stands and displacing other species. Ease of establishment, precise stocking control, rapid early growth, and the promise of shortened rotations are the major attractions. Results are usually excellent but there have been some problems in nursery practices. Early root development in planted stock is another related major concern.

Continued progress in regeneration, whether natural or artificial, is highly dependent on systematic reviews of performance.

INTRODUCTION

The successful regeneration of lodgepole pine, in the form of its most widely distributed variety (*Pinus contorta* var. *latifolia* Engelm.), is still an art. But our ability to create stands of healthy, well-distributed trees has been raised to a level of high achievement when judged by North American standards. This feat has been accomplished by a variety of scientific and operational advances that have taken place since regeneration of the species first because a subject of concern, with the assistance of the lavish reproductive capabilities of lodgepole pine.

Our aim in this paper is to describe the most important of the advances made since the last symposium in 1973, and to assess prospective advances. Using as our starting point the summaries of North American knowledge and United States practice prepared by Lotan (1975*a*, *b*) and Alexander (1974), and complemented by the Canadian work of Smithers (1961), Armit (1966) and Clark (1974), we move on to examine the most notable trends in regeneration practices. We deal in greater depth with specific advances in natural regeneration, direct seeding, and planting, using the recently issued summary reports by Lotan and Perry (1983) and Reid, Collins Nurseries Ltd. (1983) as sources of references and ideas. In our conclusion we make some proposals for silvicultural emphasis in the future.

TRENDS IN REGENERATION PRACTICES

Western foresters on both sides of the border were quick to recognize that lodgepole pine reproduced best in the open on disturbed soil and that the prolific seeding habit reduced the problem of regeneration after clearcutting. Nevertheless, it wasn't until the 1950's and early 1960's that resource exploitation and partial cutting practices began to fade, and even-aged management by means of clearcutting was accepted as the best way to convert old-growth pine to productive young forests. By the time of the last symposium, Lotan (1975*b*) had noted the universality of clearcutting as a regeneration method. He also noted public concern about the environmental impact of clearcutting lodgepole pine, particularly in the central and southern Rockies where foresters were under pressure to recognize non-timber values in management. This had led to the work of Alexander (1972, 1974), which provided the first detailed guidelines for maintaining continuous cover in lodgepole pine stands occupying sites of special value for recreational or hydrological purposes.

Interest in more intensive management of lodgepole pine, involving substantial investment of resources in seedling production and planting, was restricted to areas where natural regeneration had failed, to experimental situations, and to locations such as Sweden, Ireland, and New Zealand where lodgepole pine had been introduced and shown promise as an exotic plantation species.

While the predominant theme today is still low-cost timber management of the lodgepole pine resource by way of clearcutting, there have been some significant changes in the last ten years. Better utilization practices, changing logging machinery, stricter reforestation standards, and research extension efforts have created a greater silvicultural awareness of regeneration needs among foresters in all parts of the species' range. Serotiny is no longer a foreign word, and overstocking is as much a concern as understocking. There has also been a surge of interest in intensive management, partly in response to rising lodgepole pine timber values and also as a reaction to concern over future wood supplies. In terms of regeneration practices this means that foresters are now advocating the use of planting as a means of improving seedling distribution and density in young pine stands, and as a means of reducing regeneration delays. The rapid early growth of planted pine has also prompted British Columbia foresters to plant pine on large numbers of sites where the old-growth pine component was negligible or nonexistent. These trends have led to a major expansion in the use of planting stock, especially in Canada as follows:

	1973	1983
	thousands of seedlings	
B.C.	5,400	19,650
Alberta	1,700	4,250
Idaho, Montana, Oregon, Utah, Washington	not available	9,940

Thus, while natural regeneration is still the predominant regeneration technique, planting of lodegpole pine is much more prominent than it was ten years ago and our paper reflects this fact.

ADVANCES IN NATURAL REGENERATION

Although lodgepole pine stands are considered to be relatively simple to regenerate, the forest manager must still consider a wide range of factors and weigh their influence before making any regeneration decision. To assist the manager, Lotan and Perry (1983) have distilled experience from many quarters and prepared a simple guide to the decision-making process, concentrating on natural regeneration. They have proposed that forest managers ask four questions before deciding which combination of silvicultural system and cutting practice to use on any given site. In summary form they are:

1. Is the natural regeneration potential sufficient to meet stocking goals? If the goals are set at a high level, or potential is low, artificial regeneration may be required; otherwise, managers must consider manipulation of seed supply and seedbed in both harvesting and site preparation operations to ensure that the regeneration potential is realized.
2. Are serotinous cones available and sufficient? If not, and natural regeneration is planned, cutting practices must be adjusted to ensure adequate seed-fall either from seed trees or cut block edges in the first years following harvesting.
3. Is dwarf mistletoe (*Arceuthobium americanum* Nutt. ex. Engelm.) a problem? If so, cutting and site preparation practices must be adjusted to minimize future infection from old-growth stems (whether in cut block, or on the boundaries) and from advanced regeneration.
4. Is windthrow a hazard? If so, cutting practices must be modified to minimize the risk.

Lodgepole pine windthrow problems have not been the subject of any innovations since the work of Alexander (1974). However, there have been several advances in the past ten to fifteen years that assist foresters both in answering the first two questions on natural regeneration potential, and in coping with dwarf mistletoe. Our ability to estimate the potential for natural regeneration on any given area has been improved substantially as a result of experimentation and careful observation of operational results. Site preparation techniques have been greatly improved, especially in Canada, as have measures for protecting naturally regenerated stands from infection by dwarf mistletoe.

Estimating the Potential for Natural Regeneration

The potential for natural regeneration can be assessed if the supply of cones and seed is known, and if the forest manager has some idea of the amount of seed required to produce satisfactory stocking after harvesting under a variety of site and seedbed conditions.

Prediction equations using stand variables have been developed to estimate the amount of cones on an area basis and, when combined with an estimate of the number of viable seeds per cone, they can be used to calculate a value for seed supply prior to harvesting (Lotan and Jensen, 1970; Lotan, 1975*b*). Harvesting reduces the seed supply of serotinous stands because cones are buried, crushed, or removed from the site. Clark (1974) found the reduction to be between 90% and 95% on cutovers in southern British Columbia, but Lotan and Perry (1983) suggested the loss could be much less. In a more recent study Clark (1984) reported on cone distribution after logging operations using feller-buncher/grapple-skidder equipment. He found that minimum stocking levels were reached on most areas, but recommended in addition cone bearing slash should be left to ensure more rapid and more consistent regeneration results.

Seed supplies in non-serotinous stands can be calculated by using the same estimation procedures, with a reduction factor to account for the average ten-year production of cones that is stored in serotinous stands (Lotan and Perry, 1983). Seed traps can be used to obtain better estimates (Dahms and Barrett, 1975).

Post-harvesting seed supply estimates can be converted into a value for potential seedlings with the use of the seed/seedling ratios developed for a range of site and seedbed conditions by several authors, and summarized by Lotan and Perry (1983). The example provided in table 1 shows how a forest manager might use this information to make a regeneration decision.

Table 1. – Estimating regeneration potential

Suppose site has moderate moisture and temperature conditions, and vegetative competition on Douglas-fir/Calamagrostis site type is moderate and mineral soil exposure from winter logging on snow is limited.

STEP 1 Cone supply = 690,000/ha

STEP 2 Viable seed content = 24 seeds/cone

STEP 3 Potential seed supply = step 2 × step 3 = 16,560,000/ha

STEP 4 Reduction factor for winter logging (feller-buncher/grapple-skidder) operations, with eradication of advanced regeneration infected with dwarf mistletoe = 0.10

STEP 5 Post-harvesting seed supply = step 3 × step 4 = 1,656,000/ha

STEP 6 5th year seedling/seed ratio
  a. without site preparation to improve seedbed conditions = 1,000:1
  b. with site preparation = 100:1

STEP 7 Regeneration potential:
  = step 5 step 6a = 1,656 trees/ha
  step 5 step 6b = 16,560 trees/ha

Conclusion: Manager can either forego site preparation and plan to improve number and distribution of seedlings through planting, or modify site preparation procedures to reduce total mineral soil exposure. Juvenile thinning may be required in either case.

A post-harvesting approach to estimating regeneration potential has been developed by Glen (1979) and is used in the interior of British Columbia. Site preparation treatments are recommended on the basis of the distribution of cones, their total numbers, and the numbers of cones on suitable seedbeds (see next section).

One major problem with both methods of estimating regeneration potential is that their reliability has not been fully tested. Part of the reason for this is that managers must wait a long time between the survey of potential, site treatments (if any), and the completion of stocking. Crossley (1976) and Johnstone (1976) have shown that ingress of regeneration takes place for at least 15 years in the boreal and sub-alpine forests of Alberta. In British Columbia and Alberta regeneration surveys are commonly delayed for 5 to 7 years after harvesting or site preparation, by which time it is estimated that only 60-80% of regeneration has occurred.

There are at least two other factors that should make readers wary of the unqualified application of either method of estimating regeneration potential. The fact that conifer seed predation by small mammals can reduce seed supply substantially has been known for some time, but Sullivan and Sullivan (1982) have shown that predator populations and damage from seed loss vary considerably on lodgepole pine cutovers in southern B.C. Heavy predation on one cutblock could convert a potential success story into a miserable failure. Changing logging techniques may also remove more seed from the site than previously expected. In another study from southern B.C., Clark (1984) has reported a study of the effect of whole-tree logging using feller bunchers and grapple skidders on subsequent pine regeneration. Initially, there was fear that the numbers of serotinous cones, and therefore regeneration potential, would be reduced because entire trees were being removed to the landings with little ground contact. Results to date show no reasons for special concern.

Improving Seedbed Conditions and Cone Distribution

Efforts to improve seedbed conditions and cone distribution have been concentrated in Canada because the climate is moist and cool, litter accumulations on lodgepole pine sites are often substantial and additional mineral soil exposure is essential for successful natural regeneration, particularly after harvesting on snow. The early attempts to improve germination were based on experience with blade scarification on spruce sites – a practice that proved to be expensive. In Hinton, Alberta, the idea of using tractors to drag heavy anchor chains to break down cone-bearing slash and deposit cones close to mineral soil was introduced in the early 1960's. This practice, drag scarification, became accepted in British Columbia by 1970 as regeneration results from broadcast burning proved to be negative (Clark, 1974), and better stand utilization practices reduced the need for slash disposal. By the mid 1970's early results from drag scarification were encouraging (Glen and Ackerman, 1978; Thompson, 1978) but quite variable (see table 2), and studies were initiated to examine ways of improving the reliability of the technique.

Table 2. – Drag scarification results from central interior of British Columbia[1]

Regeneration Density Class	Areas Surveyed
----stems/ha----	----%----
less than 1,000	7
1,000- 2,000	13
2,000- 4,000	31
4,000- 6,000	21
6,000-10,000	18
more than 10,000	10
	100

[1] Based on 73 areas, data from Glen and Ackerman (1978)

Detailed guidelines for drag scarification in British Columbia have been prepared by Glen (1979). They are based on the following factors:

1. Slash rating, which influences choice of scarification equipment;
2. Number and distribution of cones, which influence choice of regeneration method, scarification equipment, and timing of scarification;
3. Depth of duff, which influences choice of equipment and its weight;
4. Slope, which influences choice of method and direction of operations;
5. Stump density and height, which influence choice of method; and
6. Soil moisture, which influences choice of towing equipment and timing of scarification.

Recommendations are based on the need to avoid both overstocking and understocking. Examples are shown in table 3 and the principal types of equipment used are shown in figure 1.

Table 3. – Drag scarification recommendations for a mechanically logged lodgepole pine stand (from Glen, 1979)

	No. of Cones After Harvesting[1]		
Cone Distribution	Total	On Satisfactory Seedbed	Recommendation
Good	10+	7+	Use light anchor chain one year following harvest to uproot germinants.
Good	3-10	less than 3	Use heavy anchor chains in spring following harvest to increase suitable seedbed.[2]
Patchy	3-10	less than 3	Use heavy and light anchor chains to increase seedbed and improve chances of germination.
Good	10+	less than 3	Use sharkfin drums to produce limited increase to seedbed and concentrate regeneration in rows.

[1] Based on survey using 5-m^2 plots

[2] Alberta Forest Service recommends delaying scarification until pine slash is well dried to improve distribution.

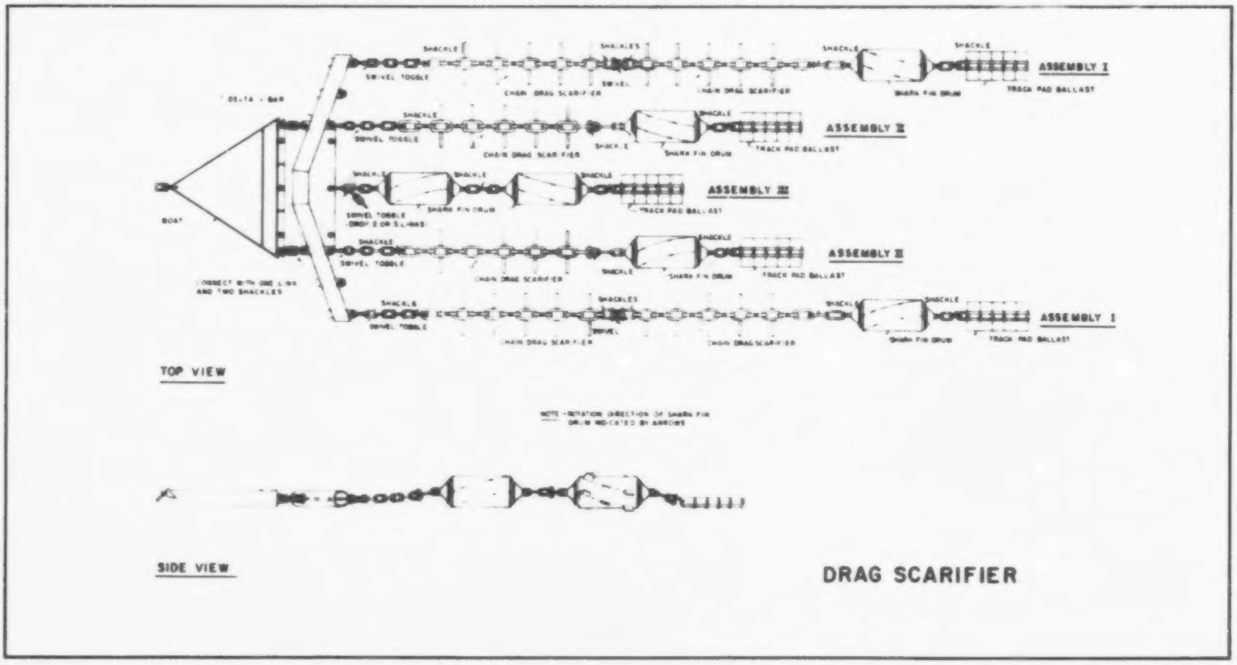
SHACKLE
SHACKLES
SWIVEL TOGGLE
SWIVEL
CHAIN DRAG SCARIFIER
SHARK FIN DRUM
TRACK PAD BALLAST
ASSEMBLY I
DELTA - BAR
ASSEMBLY II
ASSEMBLY III
SWIVEL TOGGLE (DROP 2 OR 3 LINKS)
BOAT
CONNECT WITH ONE LINK AND TWO SHACKLES
TOP VIEW
NOTE - ROTATION DIRECTION OF SHARK FIN DRUM INDICATED BY ARROWS
SIDE VIEW
DRAG SCARIFIER

Figure 1. – Three examples of drag scarification equipment combinations (from Glen, 1979).

The scarification guidelines are based almost entirely on experience and basic knowledge of the requirements for successfully regenerating lodgepole pine, but trials have been established to check their validity (Glen, 1978; Herring, 1981; Vietnieks, 1983).

Reducing Risk of Mistletoe Infection

If regenerating stands are threatened by dwarf mistletoe infection, forest managers can now refer to a great deal of accumulated knowledge (e.g. Scharpf and Parmeter, 1978) before deciding how best to reduce the risk to an acceptable minimum. Special silvicultural extension efforts have been made (Baranyay and Smith, 1972; Hadfield and Russell, 1978), and local guidelines prepared (e.g. Vyse, 1981). As a result, foresters on both sides of the border now plan layout of cutblock boundaries in mature pine with the risk of infection from edge trees kept in mind. Furthermore, the removal of residual stems after harvesting has become common practice in British Columbia. Large live residuals must be cut by the logging contractors, and a variety of methods, including hand cutting, drag scarification, and machine crushing, are used to destroy the smaller stems. Broadcast burning has been proposed specifically for sanitation purposes (Muraro, 1978) but is not practised because of the risk of an undesirable reduction in seed supply (Clark, 1974).

ADVANCES IN DIRECT SEEDING

If natural regeneration of lodgepole pine has been judged as unlikely or as having failed, planting is considered to be a much better artificial regeneration option than direct seeding. Results from seeding pine have not been good and consequently the method has been all but abandoned in every part of the natural range except Alberta. There, seeding is used to supplement the natural seed source after scarification, but the annual area treated is small (Ferdinand, 1983).

This situation might change if utilization and harvesting developments lead to an increase in natural regeneration failures. Rising plantation establishment costs, or limited seedling supplies, might also lead to decisions that prohibit planting on low productivity pine sites. These last two factors have already taken effect in British Columbia and there has been a minor resurgence of interest in two spot-seeding techniques: the use of seeding in conjunction with patch scarification equipment, which improves germination conditions; and the use of the Finnish shelter cone method, which improves germination and growth conditions. The combination of spot seeding with patch scarification has shown promise in Ontario (Winston and Schneider, 1977) and should work elsewhere, although trials conducted to date have not been successful (Ferdinand, 1983). The shelter cone method, which forms a mini-greenhouse over the seed and seedling, has shown more promise in British Columbia[1], but suffers from the drawback of requiring careful manual placement. It may prove useful in evading short-term limits to seedling production.

One major factor contributing to a lack of success in direct seeding operation is seed predation by small mammals. Sullivan and Sullivan (1982), have found that the application of alternative and preferred food in the form of sunflower seeds will increase the survival of lodgepole pine seed by four times or more on cutovers with high animal densities. Spot or row seeding combined with an alternative food treatment deserves a trial on low-productivity sites.

ADVANCES IN PLANTING

Practical experience suggests that lodgepole pine is easy to establish as a planted seedling throughout the west. There are many healthy plantations spread over a wide variety of sites across the species's natural range and beyond. Part of this success is attributable to the natural resilience of lodgepole pine, but it is evident to us that much has been learned about establishing plantations in the last decade. A number of studies dealing with ways of improving stock production and planting programs have been published. Not all the ideas contained in those studies have been implemented, but in total the increase in knowledge represents an advance at least as much as that made in actual area planted. We have chosen to focus on a few key topics of special interest to field foresters.

Increasing Survival on High Moisture Stress Sites

Adequate survival can be difficult to obtain on sites where high moisture stress is a major factor contributing to mortality. Drought-attributed mortality of planted seedlings commonly occurs on south slopes in northern Wyoming, Montana and Idaho (Lotan, 1964; Alexander, 1974). The ability of seedlings to avoid desiccation or drought is highly dependent on fast root extension. The absence of lodgepole pine on very dry sites has been attributed to slow initial root elongation; but once established, survival is favored by a sensitive inherent control of water loss (Lopushinsky, 1975; Brix, 1978). Thus, nursery production of seedlings with a high root-regeneration capacity, and handling procedures which preserve the viable root systems, should increase drought avoidance ability.

Provenance variation in survival and growth during drought, and in rate of photosynthesis of lodgepole pine seedlings (Sweet and Wareing 1968; Dykstra 1974) and family variation in water stress resistance (Perry *et al.*, 1978) indicates the potential for control of losses on dry sites through tree improvement programs.

There is also evidence that "large" stock will perform better than "small" stock on drought-prone sites (Baerr *et al.*, 1977) and this is supported by studies of other species. With Douglas-fir this is a response to shoot/root ratio rather than to absolute size.

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[1] Unpublished results from silvicultural trials made available by D. Wallinger, Silviculture Branch, Ministry of Forests, Victoria, B.C.

Reducing Root Deformation and Juvenile Instability

Root deformation and instability of planted lodgepole pine trees is a topic of recurring interest and debate (Van Eerden and Kinghorn, 1978). The instability of planted lodgepole pine trees is attributed to the shortage of well-distributed primary lateral roots and the inability of the trees to regenerate new ones (Burdett, 1979*a*; Selby and Seaby, 1982). It may occur with both bareroot and container-grown stock, though the nature of this deficiency in the two stock types is different.

All container systems presently in use, regardless of their design features, create a vertical root cage (Van Eerden, 1982). As lodgepole pine does not produce adventitious roots, container-grown seedlings have markedly distorted root systems. In the early years of rapid height growth these distortions *may* predispose the planted trees to basal sweep, instability and, under certain climatic and soil conditions, toppling or windthrow.

Several techniques have been tested to eliminate the characteristic effect of container on root form. A chemical root pruning technique involving the use of containers coated on the inside with latex paint containing cupric carbonate has been developed (Burdett, 1978). The wall coating inhibits root growth and thereby prevents lateral roots growing down or around the container wall. The arrested root tips resume growth when the trees are removed from the container. The chemically pruned trees show enhanced side root development and height growth after outplanting compared with the controls (McDonald *et al.*, 1982; Burdett *et al.*, 1983). The chemical pruning does not, however, appear to be universally applicable without modification. In particular, it is useful only when the container is small (McDonald *et al.*, 1982). To counter these problems, Burdett (1982) has proposed a mechanical method for box pruning the roots of container-grown stock. Seedlings are grown in slot-sided trays which permit lateral root pruning on one or more occasions before extraction.

Seedlings grown in bareroot nurseries can also have deficient root systems. Lifting and transplanting reduces the number of primary lateral roots, and survivors become thickened and severely disturbed. Possible solutions include wrenching and lateral pruning and the initiation of more lateral roots by auxin treatment. Watering soil-grown lodgepole pine seedlings with auxin solution has induced the development of a large number of primary lateral roots (Selby and Seaby, 1982).

Poor planting of bareroot stock can increase the risk of instability by producing either a compressed bilateral root system in the planting slit or a unilateral root distribution (J roots) in which the roots become balled in the planting hole. The problem is much reduced with container stock.

After outplanting, any root problems that may exist can be aggravated by slow root growth and rapid early height growth. Basal bowing or toppling are likely consequences (Lines and Booth, 1972; Reid, Collins Nurseries Ltd., 1983). Site preparation techniques that encourage root growth through favorable increases in soil temperatures, aeration and nutrient availability can alleviate this problem. McMinn (1978) has found that the root mass of lodgepole pine bareroot seedlings planted in mixed microsites where (vegetation and duff were incorporated into mineral soil) greatly exceeded that of seedlings planted in blade scarified or untreated plots (table 4). The root/top and root area/crown height ratios of the container lodgepole pine seedlings were improved by planting in mound microsites rather than patch microsites (Martinsson, 1983).

Table 4. – Root mass of lodgepole pine bareroot seedlings five years after outplanting in variously treated sites:[1]

Site Treatment	Growing Seasons After Planting				
	0	1	2	3	5
untreated	0.7 a	1.0 a	2.1 a	5.5 a	39.7 a
blade scarified	0.7 a	1.2 b	3.3 ab	6.6 b	63.4 b
mixed	0.7 a	1.3 b	4.0 b	13.0 c	103.3 c

[1] from McMinn 1978

Although the effects of root deformations in planted stock of lodgepole pine have led to serious losses in some locations (Chavasse, 1978; Burdett, 1979a), the overall risk of significant economic losses can be small if the simple evasive techniques discussed above are implemented (Van Eerden, 1982).

Improved Quality of Container Seedlings

Much has been learned about container stock production over the past ten years. Guidelines on rearing high quality, containerized lodgepole pine are now available in several compilation reports (Tinus and McDonald, 1979; Carlson, 1983). This knowledge is augmented by the numerous papers on refinements of the techniques and by the regional recommendations presented in the proceedings of two symposia on containerized production (Tinus *et al.*, 1974; Scarratt *et al.*, 1982). Several advances deserve specific mention here.

Performance studies of containerized seedlings uniformly show that the largest plant that can be grown, handled, and planted economically produces the best growth and highest biomass after outplanting. The survival and growth was positively related to increased stock age, stock size, and container size (Endean and Hocking, 1973; Dobbs, 1976; Walker and Ball, 1981). The relationships found show that the hazardous plantation establishment period can be shortened considerably if larger stock, produced over longer greenhouse rearing periods, or larger containers are used. However, seedlings from small-volume containers (e.g. 40 cc) have shown adequate growth on a wide range of sites in British Columbia (Vyse, 1982).

Induction of Cold Hardiness for Cold Storage for Overwintering Outdoors

Winter damage to lodgepole pine container seedlings overwintered outside, usually at the nursery site, adversely affects the seedlings and reduces the quality of stock. The conditioning process to induce adequate hardiness of lodgepole pine seedlings prior to extracting and packaging for cold storage is described by Matthews (1982). Cold hardiness can be enhanced by exposure to long-night (short-day) treatments developed for lodgepole pine by Rosvall-Ahnebrink (1982) and for other species (e.g. Colombo *et al.*, 1982). Zalasky (1983*a*, *b*) has designed a complete system for rearing, conditioning, and overwintering lodgepole pine container seedlings, and has also provided the structural specifications and operational procedures for a simple unheated storage facility. Further progress in this area is hindered by the lack of a rapid test for cold hardiness.

Enriched CO_2 Environment

Lodgepole pine responds positively to enriched CO_2 levels, and the enhancement of CO_2 concentrations appears to be a viable treatment for reducing the time needed to produce a seedling of targeted size. The CO_2 concentrations most often used in greenhouses range from 800 to 1500 ppm compared to the ambient level of 330 ppm. Enrichment of CO_2 to a concentration of approximately 1320 ppm reduced the length of growing time for lodgepole pine in greenhouses from 16 weeks to 14 weeks, based on time required to attain a target average height (Canham and McCavish, 1981). The effect was enhanced by increased nutrition. In another study, after 20 weeks of growth under controlled environment, total biomass was approximately five times greater in seedlings grown at 1000 ppm CO_2, than for seedlings grown at 330 ppm CO_2 (Higginbotham *et al.*, in press). Root biomass increased 15 times in the same seedlings. A further increase in CO_2 concentration to 2000 ppm reduced growth of seedlings.

Accelerated Growth by Extended Photoperiod

Lodgepole pine seedlings grown for six months under continuous photoperiod were ten times taller, and 200 times heavier than the control after six months of initial growing period (Wheeler, 1979). The excellent root system developed on treated seedlings and the resultant low shoot/root ratios were correlated with improved growth and survival after outplanting, and treated seedlings maintained an accelerated growth during the two growth seasons following outplanting. The immediate application of continuous photoperiod treatment may be hindered by large intraspecific variations in response to the treatment (Perry and Lotan, 1978).

Use of Growth Inhibitors and Retardants

The potential use of growth inhibitors and retardants for altering shoot/root ratios of containerized lodgepole pine, and thus enhancing survival after outplanting, and for reducing the rootbound effect of held-over container seedlings has been suggested by Weston *et al.*, 1980). Ancymidol and Phosphon could be used to reduce the shoot/root ratio, and Ethrel and CCC (Cycocel) treatments are recommended for use on held-over plants.

Mycorrhizal Inoculations

Another possible method for improving survival and growth of lodgepole pine after outplanting is to inoculate seedlings with mycorrhizal fungi. Techniques are now available for artificially inoculating containerized seedlings with pure cultures of selected mycorrhizal fungi. Twenty-two different fungi, indigenous in soils of the Pacific Northwest, were shown to have the ability to form ectomycorrhizae on lodgepole pine (Molina and Trappe, 1982). Lodgepole pine seedlings in containers have been successfully inoculated with several ectomycorrhizal fungi (table 5).

Table 5. – Successful ectomycorrhizal inoculations of container-grown lodgepole pine seedlings

FUNGUS	Evidence for Seed Source Variability
Pisolithus tinctorius (Molina, 1979; Grossnickle and Reid, 1982)	Alberta[1] Colorado (Cline and Reid, 1982)
Suillus granulatus (Grossnickle and Reid, 1982)	Colorado (Cline and Reid, 1982)
Rhizopogon luteolus	Colorado (Cline and Reid, 1982)
Laccaria laccata (Molina, 1980)	Alberta[2]
Cenococcum geophilum (Molina, 1980; Grossnickle and Reid, 1982)	Not known
Hebeloma crustuliniforme	Alberta[2]

[1] J. Dangerfield, Research Branch, Ministry of Forests, Victoria, B.C., pers. Comm.

[2] S. Navratil, unpublished data.

Both host seedling genotype and fungal species ecotype influence the degree of ectomycorrhizae formation, as well as the host seedling growth response. These results emphasize that consideration must be given to seed source, fungal species and different isolates of the fungus used for inoculation to insure optimal mycorrhizal development and seedling growth.

Seedling growth response to mycorrhizal inoculation in the rearing phase is highly variable: inoculation may increase or reduce the biomass of seedlings shoots and/or roots. In the study by Cline and Reid (1982) the amount of ectomycorrhizal infection with *Pisolithus tinctorius* and *Suillus granulatus* was positively correlated with dry weight and shoot/root ratios of lodgepole pine seedlings. The effects of mycorrhizal inoculations on growth and survival of lodgepole pine after outplanting on reforestation sites are not yet known, but on a high-elevation mining site lodgepole pine seedlings inoculated with *S. granulatus* had greater growth rates than seedlings inoculated with other fungi or control (Grossnickle and Reid, 1982).

Frequent applications of concentrated soluble fertilizers in containerized production may inhibit mycorrhizae development of seedlings, and low fertility schedules or slow-release fertilizers may be needed for inoculations with sensitive fungi such as *P. tinctorius*.

Improved Quality of Bareroot Stock Production

In recent years much has been done to speed production of bareroot planting stock and, at the same time, to improve the quality of that stock.

Van den Driessche (1982) investigated the effects of different seedbed spacing on lodgepole pine growth in the nursery and after outplanting, and examined the relation of spacing to nitrogen supply. Treatments consisted of spacing the germinated seedlings (1, 2, 4, 8, and 12 cm in drills 15 cm apart) and using three levels of nitrogen supply (60, 140, and 235 kg/ha). Spacing of 2 cm and more in drills 15 cm apart increased root collar diameter and dry weight of 2-0 year seedlings, but shoot length was only significantly increased at the 8- and 12-cm spacing. Each increase in nitrogen fertilization increased the size of seedlings as well as the amount of new shoot growth after outplanting. Much of the improved growth after planting was explained in terms of increased seedling size. At the highest level of N supply (235 kg/ha), increased spacing to 4 cm did not greatly reduce total yield of seedlings with root collar diameter greater than the minimum acceptable size of 3 mm. Thus, the combination of fertilization plus increased spacing improved quality without materially reducing yield of seedlings per unit area of nursery.

A new technique for enhancing production of bareroot seedlings has been tested in the United Kingdom. Polyethelene tunnel cloches with buried edges to cover seedbeds effectively reduced the time for producing planting stock by one year. The results show that it is possible to consistently produce one-year-old lodgepole pine seedlings sufficiently tall and sturdy for outplanting (Thompson and Biggin, 1980; Biggin, 1983).

The survival of planted bareroot lodgepole pine has been found to be strongly related to root growth capacity (Burdett, 1979*b*). Accordingly, a method for measuring root growth capacity of bareroot lodgepole pine seedlings has been adopted by the British Columbia Forest Service as the basis for nursery quality control. The method is a modification of the procedure reported by Stone and Jenkinson (1971); however, it requires less time and less labor to complete. Test seedlings are grown for no more than a week under conditions that are considered optimal for root growth, and are then assessed for new root growth.

Careful assessment of seedling morphology can be a useful criterion for estimating the potential of a plant for shoot growth and biomass production in the following year. Thompson (1976) suggests that it may be advantageous to modify the growing conditions to produce one-year-old plants that are short, but have a rosette containing a large number of primary leaves, and that have the potential to produce a large shoot after planting.

Comparisons of storage regimes of bareroot stock show that overwinter storage of fall-lifted lodgepole pine at a sub-freezing temperature results in survival and growth rates equal to or better than those obtained with conventional spring lift and cold storage procedures. Operationally, the frozen storage technique has many advantages for nursery operations and has been widely adopted in Canada and the U.S. Best results are achieved if the seedlings are lifted and preconditioned at above-freezing temperatures for 3-4 weeks prior to overwinter frozen storage[1] (McDonald *et al.*, 1983). However, the relationship between time of lifting and post-planting performance is critical. New methods for determining the physiological readiness of lodgepole pine for fall lifting, such as frost hardiness tests [2] and root growth curves (Navratil, 1984), are becoming available.

Planting freshly lifted stock late in the planting season after most stem elongation had taken place is biologically feasible and may give survival rates well above those of trees coming out of long-term storage (McDonald *et al.*, 1983). The biological potential for late summer planting is suggested by the bimodal pattern of seedling root growth (figure 2). However, the hot planting is operationally difficult because stock must be treated delicately and replanted very soon after lifting (1-2 days) to avoid severe mortality.

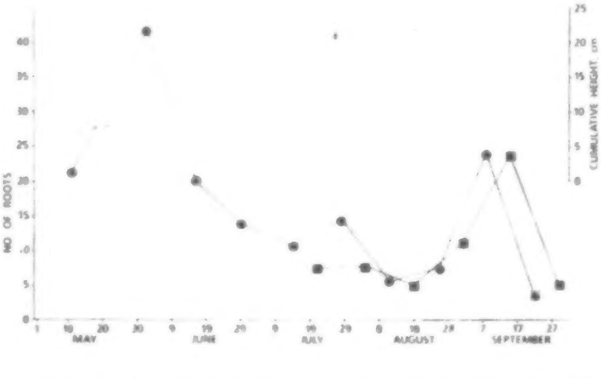

Figure 2. – Root regeneration (number of 3-10 mm long root tips) and height growth of rising 2-0 lodgepole pine seedlings in Pine Ridge Forest Nursery, Alberta

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[1] S. Navratil, unpublished data.

[2] D. Simpson, Kalamalka Research Centre, B.C. Ministry of Forests, Vernon, B.C., pers. comm.

Performance of Container and Bareroot Seedlings

A number of studies of the field performance of container-grown and bareroot lodgepole pine seedlings have been completed in the interior of British Columbia. Evaluations of 6- to 10-year-old plantations planted under operational and research conditions reached the same overall conclusion: lodgepole pine container-grown seedlings survived and grew at least as well as bareroot seedlings (Gardner, 1982; Vyse, 1982). In fact, the data indicate the potential biological superiority of the container-planting systems over the bareroot method in achieving a high survival rate. Under operational conditions, the probability of achieving a survival rate higher than 90% was greater for container (styroplug) seedlings (Vyse, 1982) than for bareroot seedlings. Container seedlings produced the highest survival ratio of any of the stock tested in a research study reported by Gardner (1982). The initial height advantage of bareroot stock was maintained or increased (figure 3), but the similarity in growth rate of both types of stock suggests that this difference may be decreasingly significant with advancing age of plantations.

Three- and five-year results from field performance trials in Alberta confirm the British Columbia results that container-grown (styroplug) seedlings have higher survival rates than bareroot, and growth rates are comparable (Walker and Johnson, 1980). Growth curves from lodgepole pine plantations in west central Alberta attest to the similarity of height growth rate of container or bareroot stock and wildlings of the same age (Hellum, 1979).

From these field trials it appears that the commonly held view about superiority of bareroot stock may not be valid. The Canadian results support the conclusion that lodgepole pine seedlings grown in small-volume (40 cc) containers are capable of equaling the performance of 2-0 bareroot stock over a wide range of sites.

Improved Mechanical Site Preparation for Planting

Many research studies have shown that the method of mechanical site preparation and the resulting quality of planting microsite can considerably affect survival and growth of seedlings. Soil temperature, soil moisture and aeration, light, supply of nutrients, and availability of microbial symbionts vary with microsite and have been shown to directly influence seedling performance. These results have been adopted in practice wherever lodgepole pine is planted. Swedish spot scarifiers are currently preferred for light scarification. The normal objective is to create between 1250 and 1600 plantable spots per hectare (Ferdinand, 1983). On areas with significant amounts of brush, dense grass, or heavy slash a more intensive site preparation is required. For highest probability of success, individual planting spots are hand-scarified; however, a proper placement of scalps may be important on droughty sites and steep slopes (Lotan and Perry, 1983).

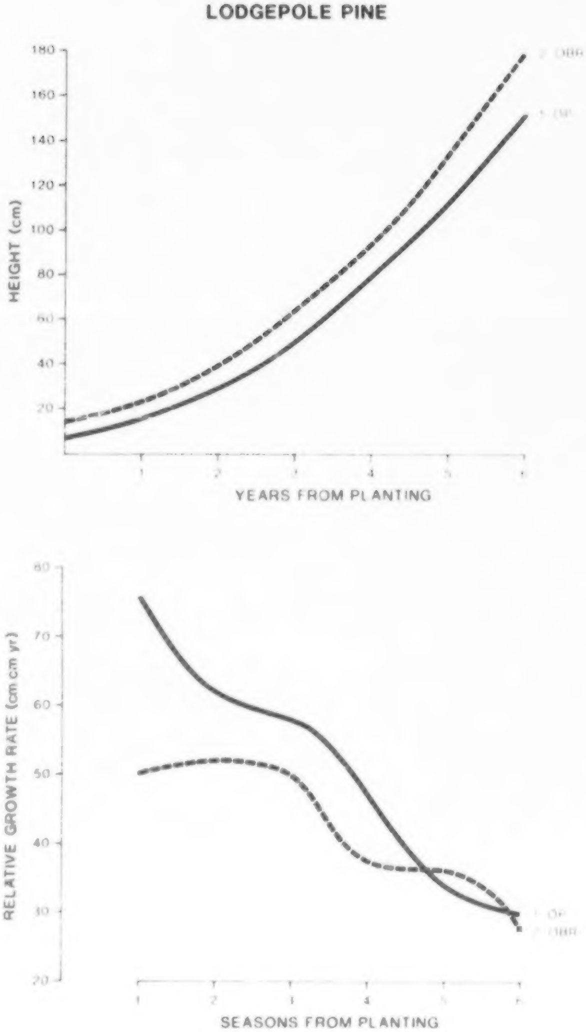

Figure 3. – Performance of operational planted seedlings in central interior of British Columbia (Vyse, 1982).

Trials with lodgepole pine and other pine species demonstrated the advantage of planting on mounds, inverted patches, and capped inverted patches, all of which increase soil temperature and favor the root growth and initial establishment of seedlings (Soderstrom, 1981; McMinn, 1982; Sutton, 1983). A new generation of site preparation equipment that produces planting spots which are responsive to the biological needs of seedlings (such as active topsoil agitators and mounding units), is becoming available. Still, if progress with mechanical site preparation is to continue, more information is needed on the interactions between microsite factors and survival and growth of lodgepole pine.

FUTURE PROGRESS IN REGENERATION

Although our survey of advances in the last ten years has revealed a number of instances where research work and innovative operations have overcome, or promise to overcome, biological and managerial obstacles to regeneration success, we think that further progress is always possible. Lodgepole pine planting can be expected to increase and a number of initiatives could be pursued in efforts to improve stock production. We anticipate that there will be substantial benefits gained with the production of stock of a higher growth capacity, a shaped root system, and with site specific mycorrhizal symbionts. More effective control of natural regeneration would reduce the overstocking problem. On sites of low productivity spot seeding offers potential benefits. However, it would be wrong to emphasize these essentially minor modifications to existing systems without drawing attention to a major deficiency in lodgepole pine regeneration programs.

As regeneration efforts expand and the system of interconnected activities becomes more complex, the need for systematic reviews of performance becomes more pressing. Managers need an improved flow of information to ensure that performance, in terms of goal attainment and resource expenditure, meets objectives. Unfortunately, most regeneration programs that we know of suffer from insufficient information feedback, and the western lodgepole pine programs are no exception. As an example, consider the current controversy over planting lodgepole pine in north central British Columbia. Proponents of planting argue that the benefits of increased control over early spacing and uniformly rapid growth offset extra costs. Natural regeneration advocates claim better early growth and reduced costs, and point to juvenile instability in plantations. No resolution of the argument is in sight because the background performance data is not available, either from operational programs or from research studies.

In order to upgrade natural regeneration programs, researchers and managers should concentrate on obtaining better information about the relationship between estimates of regeneration potential, seedbed conditions, and measured regeneration success by site. Faster and more complete monitoring of planting programs would help us learn from past mistakes and successes. Systematic efforts should be made to relate performance of various stock types to measures of stock quality at various stages from nursery to planting site, and to measures of environmental stress on those sites. Such initiatives, we submit, will provide the foundation needed for continued progress in the regeneration of lodgepole pine.

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LODGEPOLE PINE SEED: SEED CHARACTERISTICS, HANDLING AND USE

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and
B. S. P. Wang

ABSTRACT

Through its unique silvical characteristics of serotinous cones, lodgepole pine (*Pinus contorta* Dougl.) stands often regenerate themselves overabundantly following fire or logging, provided adequate site preparation has been carried out. However, in the absence of a sound forest management policy in the past, large insufficiently restocked or overstocked areas have been created and intensive efforts in reforestation and stand tending are required to correct the situation. To achieve this, a thorough knowledge of the cone and seed characteristics is essential.

This paper reviews the state of the art on major seed problems and discusses their implications and future needs for intensive management.

INTRODUCTION

Lodgepole pine is an important lumber and pulpwood species in western North America. It is being regenerated by seed from slash-borne cones at increasing rates. This practice is possible because of the serotinous nature of the cones. Foresters have between one-half a year and two years after logging to prepare the sites before all the seeds are shed from the cones in the slash.

The species is generally considered easy to regenerate because the slash contains so much seed that foresters always face the persistent problem of how to match site preparation to the seed available in the slash. Most new stands will be grossly overstocked and need costly thinning, if site preparation is too intensive. At the opposite extreme, cutovers do not restock themselves if site preparation is not done in time or if it is inadequate.

Planting is an expensive alternative to natural regeneration for this species. However, improved seed is beginning to be used in nurseries for seedling production, and this means the eventual development of valuable plantations with improved productivity.

All practices involved in stock production must be improved in order to reduce the costs of planting. Having a better understanding of the cone production, extraction and storage characteristics of the species will improve the control of seed quality. This will increase the efficiency of seed utilization and thereby reduce the costs of stock production.

This paper reviews cone and seed characteristics and the state of the art of seed production, maturity, handling, processing, testing, storage and utilization in order to provide background information for future improvements in seed handling and utilization. It discusses implications of these subjects in relation to future research and intensive management goals.

CONE CHARACTERISTICS AND SEED PRODUCTION

When cones are collected to provide seed for operational reforestation, all-aged cones between 2 and 30 years are frequently mixed together. These cones are variable in seed yield, in seed release characteristics, in seed viability, and in year to year variation in pollination. Since all these characteristics affect the yield and quality of seed, it is therefore important to understand as much about them as possible when planning cone collection operations.

Most stands in Canada bear closed, serotinous cones, but many stands in the U.S.A. bear non-serotinous cones. Whether the stand is serotinous or not it is important to note that annual seed production in lodgepole pine is modest, when compared to that of other conifers.

Cone Characteristics

The cones of lodgepole pine in Alberta are rarely over 7.5 cm long and weigh up to about 17 grams. Cones from Colorado/Montana have been reported to weigh as much as those of Ponderosa pine (*P. ponderosa* Laws.) (Krugman and Jenkinson 1974). Alberta cones have 100 to 130 scales and are well armed. Each apophysis bears a sharp umbo. The apophysis is commonly greatly swollen in the basal part of the cone. Cones turn silvery grey with age and by age 15 most of the brown color has disappeared. Most cones fall off before they are 30 years old (Hellum 1983). Thus, the tree keeps rejuvenating the cone material and the seed.

Individual mature trees can bear over 1,000 closed cones at a time (Crossley 1956) but trees in closed stands rarely have more than 500, and many bear less than 300 even at ages over 110 years (Hellum *op cit.*).

Most of the cones on a tree may be collected for seed extraction because, even though old cones may yield less seeds than fresh cones (Hellum and Barker 1981), they contain seeds of high viability (Wang 1978).

Serotiny

Most of what is mentioned in this article pertains to discussions of serotinous cones and only sporadic mention is made of the non-serotinous type. Serotiny implies delayed seed release and could be interpreted as a kind of imposed dormancy (Harper 1977), though the seeds themselves only have innate dormancy and usually germinate as soon as the environment permits. Seed retention inside the cones of lodgepole pine has been talked about for over 75 years (Towers 1909), but there is still much to be learned about this phenomenon (Lotan 1975).

Scale Types

The average lodgepole pine cone has three rather distinct scale types which differ in form and fecundity as well as in their flexing or opening characteristics and in their anatomy and chemical composition.

Basal Scales

Basal scales are sterile and make up about 65% of all scales, according to one study from Alberta (Hellum 1983). The average cone had about 115 scales in total. The basal scales are attached to the rachis of the cone by a very narrow stem. The stem base widens with distance from the cone's base, so that there is a gradual transition from this scale type to the next type found in the middle of the cone. The basal scales bear seed wings in some cases but are never fertile. They may also bear faint colour imprints, suggesting perhaps where seeds might have been located in earlier evolutionary times.

Basal scales flex open when their bonds are melted or broken, but they bend only in a very small elbow joint some distance from the cone rachis. Scales with enlarged apophyses tend to be sterile.

Middle Scales

Scales from the middle of the cones are wide from base to edge of apophysis and make up about 25% of the entire scale number. They are the most fertile part of the cone. These scales flex by bending along their entire length from base to tip and may bend far enough to overlap the basal scales or each other. This extreme bending may lead to some seed retention if cones are not tumbled in kilns to release the seed gradually as scales flex.

Apical Scales

The apical scales represent about 10% of the entire scale number and have about half the fecundity of the middle scales. They are narrow and bent along their long axis so that they clasp each other tightly in closed cones. The scales cannot flex except from bases. Flexing in this part of the cone is commonly hampered by slower opening of more basal scales.

Cone Scale Tissues

The average pine cone scale is made up of three layers of different tissues which act together like a trimetallic strip when cones start to open or close.

The central tissue of the scale is mainly made up of tracheids and collenchyma. The dorsal side of the scale is composed of sclereids and the ventral side of the scale has a thin layer of parenchymatous tissues and a thin layer of sclereids (Allen and Wardrop 1964, Harlow *et el.* 1964). The sclereid tissue is highly hygroscopic absorbing and losing water readily to the air. When they lose water, they contract considerably and this leads to cone scale opening just as water absorption leads to cone closure.

The thin ventral layer of sclereids simply is not strong enough to prevent scale flexing. The vascular tissues appear to work like a central backbone or pivot preventing the scale from shrinking when losing water.

Effect of Cone Age on Seed Yield and Germination

Seed yield of lodgepole pine varies greatly with cone size, parent trees, stands, geographic source, as well as seed extraction methods. Because of its unique silvical characteristic of retaining large quantities of seed in serotinous cones as a potential seed supply for regeneration, the effect of cone age on seed yield and seed quality has been studied repeatedly with a view to determining what ages of cones are worthy collecting.

Although a doubtful result was reported by Clements (1910) that seed yield in terms of number of seeds per cone appeared to increase with cone age, this was clarified by later findings by Bates (1930), Thompson (1969) and Wang (1978) who reported that there was no fixed relationship between seed yield and cone age and that variation in seed yield from cones of different ages was a reflection of the size of cone crops in different years (Figure 1). In his study with the Alberta lodgepole pine, Wang (1978) failed to find any significant effect of cone age on seed yield with possibly the exception of the cones of 10-15 years old which tend to yield slightly fewer seeds per cone than younger ones. The average seed yield varied from a low of 17.8 seeds per cone of 10-15 year-old cones to a high of 21.1 per cone of 2-year-old cones. Wang's (1978) findings were confirmed by recent results on cone production and seed yield of grafted lodgepole pine clone banks at Red Rock, near Prince George, B.C.[1].

However, when comparing seed yield on the basis of cone weight, Bates (1930) found that new cones of 185-year-old stands from southern Wyoming and western Colorado yielded 1.3 and 2.4 times more sound seeds respectively than the old cones. Recent field observations in Alberta have shown that 2-year-old cones do open in very warm fall weather, but that if the weather is not very warm the cones do not open even if fall weather in subsequent years is warmer still. This is the most likely reason why older cones were found to contain less seeds than young cones. In Alberta, Ackerman (1966) noted the colour and texture of cones change with age from a glossy, yellow-brown to a matte grey, and used such weathering effects as cone-age indices. In the province of British Columbia lodgepole pine cones older than 5 years are not considered collectable because they yield fewer viable seeds (Dobbs *et al.* 1976). However, this is probably caused by poor cone opening.

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[1] Unpublished report. Ying, C. C., J. C. Murphy and S. Anderson. 1983. Cone production and seed yield in three grafted lodgepole pine (*P. contorta* Dougl.) clone banks at Red Rock, near Prince George, British Columbia. B.C. Forest Service, Victoria, B.C.

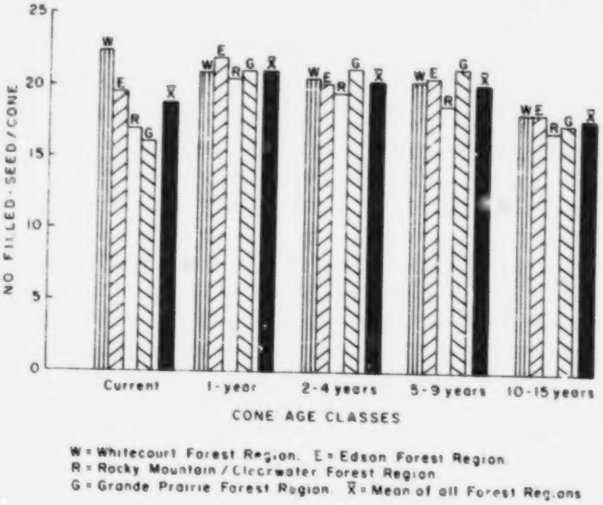


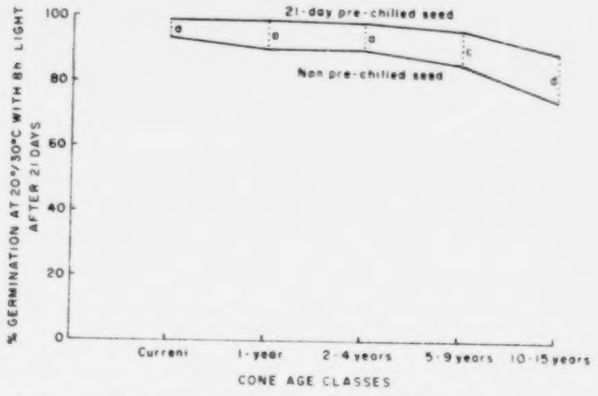
Figure 1. – Effect of cone age on yield of number of seed per cone of lodgepole pine from four major forest regions of Alberta.

As reported by Ackerman (1963) and Wang (1978), cone age had little or no effect on germination of lodgepole pine seed of Alberta sources, although seeds from the 10- to 15-year-old cone class in Wang's study showed a deeper dormancy and a slightly reduced germination of 90% as compared 96% to 99% that from younger cone-age classes (Figure 2). In an earlier study, Bates (1930) found that seeds from new cones of Wyoming and Colorado lodgepole pine stands exhibited a slightly higher average germination capacity (63% and 74%) than those from old cones (58% and 67%).

Because only about 15-20% of the cones on an average lodgepole pine tree in Alberta bear cones older than 15 years, it is doubtful if one has to worry about collecting the older, less valuable cones together with the younger cones in operational work. The efficiency of cone collection can be improved by using mechanized harvesting equipment such as cone strippers.

Seed Characteristics

Lodgepole pine seeds are 3-4 mm long, ovoid with wings of about 12 mm long. They commonly weigh between 3 and 6 mg and have a black ridged seed coat when mature. Seed



LETTERS A, C AND D REPRESENT DIFFERENCES IN TOTAL GERMINATION BETWEEN PRE-CHILLED AND NON PRECHILLED SEED IS SIGNIFICANT AT [illegible] AND [illegible] LEVEL OF PROBABILITY RESPECTIVELY.

Figure 2. – Effect of cone age on germination of pre-chilled and nonpre-chilled lodgepole pine seed from Alberta (each point is a mean of 48 replicates of 100 seeds each).

colouring develops gradually as seeds mature changing from pure white to black over a period of about one month in the fall. Empty and partly filled seeds are commonly only partly black. White and brown spots on the seed surface signify poor seed quality in most cases. The seed is black by the time it is fully developed morphologically, but considerable further chemical change is needed inside the seed for it to become physiologically mature. Factors which prevent seed maturation after full morphological development, lead to problems in the maintenance of high seed viability in storage. Such seeds are difficult to remove in cleaning operations.

Seed Production by Scale Type

The basal scales were found to bear either wings only or no sign of even rudimentary seed formation. The middle scales produced between 75% and 85% of all the seed in the cone (Hellum 1983). In other words, about 25% of the scales produce between 75% and 85% of the seed. The average middle scale produced between 1.3 and 1.5 seeds. Seed yields from other parts of the species' range than Alberta might be expected to differ (Hellum 1983).

The average apical scale produced only 0.7 seeds. None produced 2 seeds and the second seed wing commonly was reduced or lacking altogether. The scales were too narrow and too modified to be able to produce more than at most one seed. This apical part of the cone produced between 25% and 15% of the seed in the cone, again depending on the tree.

Considering cone scale types, the overall efficiency of seed production was rated between 59% and 70% for each of four seed years.

Seed Tolerance to Temperature

The seeds can stand temperatures up to 80°C and above for shorter periods (Hellum and Pelchat 1979) but extraction should probably be carried out at much lower temperatures because long-term storage may be affected if seeds are weakened by heat.

Experience from Finland and Sweden (Kangas 1942, Hermelin 1958) suggests that extraction temperatures should not exceed and preferably should be kept well below 50°C to maintain high seed viability in Scots pine (*Pinus silvestris* L.) over long periods. Lodgepole pine has been found to be more tolerant of heat than this (Hellum and Pelchat *op cit.*, Bates 1930).

Seed/Cone Production Over a Lifetime

The average lodgepole pine cone from Alberta contains between 15 and 30 full seeds judging by many years of testing seed yields in this species.[2] When cones yield less than 15 full seeds they are often judged to be non-collectable. The minimum seed count of one-half cone section in B.C. is 20 (Dobbs *et al.* 1976) but practice in Alberta suggests a count of only 6 to 8 seeds.

The accumulation of cones on living trees progresses very slowly and averages out at about 5 cones per year over a 100-year rotation period from time of first cone production (Hellum 1983). By the time the average tree is 115 years old, it still might be expected to retain about 500 cones, or 38% of the 1300 cones it can ever produce. Open-grown trees may be expected to produce more cones than trees in closed stands, as shown by Crossley (1956).

If the average cone produces 20 viable seeds and an average tree was or is able to produce 1,300 cones, then the average tree produces a mere 26,000 seeds in 100 years, or only 260 seeds per year. This cannot be considered as heavy seed production in any given year or over the life of the tree. In fact, trees commonly produce so few seeds annually that comparisons of germination among trees within stands often are impossible. However, cone production and seed yield from grafted clonal seed orchards of interior B.C. showed much greater potential than natural stands from Alberta (Ying *et al. op cit.*).

Serotiny and Its Implications for Regeneration

Critchfield (1957) and Lotan (1975) have commented on the non-serotinous habit of many stands of lodgepole pine in the United States. Such stands obviously bear only the annual crop of seeds plus a small amount of seeds which might have been retained in the cones from the previous year. Annual seed shed may still amount to over a million seeds per hectare per year, judging by the above reports. This is ample seedcast for natural regeneration should the forest floor become receptive after fires.

The serotinous stands described by Crossley (1956) in southern Alberta also shed some seed annually, but the 25,000 to 60,000 seeds (per year and hectare) are inadequate for natural regeneration unless that seeds fall onto receptive seedbeds. For successful natural regeneration slash-borne serotinous cones have to be positioned close to the ground within 15 cm to effect cone opening (Crossley 1956b, Ackerman 1966).

The serotinous stand which dies without fire to break cone bonds, such as in southern British Columbia or Alberta owing to extensive damage from the bark beetle, *Dendroctonus ponderosa* Hopk. (Safranyik *et al.* 1974), will not regenerate itself to pine until the trees fall down. The site will by then be lost to other species. Serotiny in this context is certainly a disadvantage. The serotinous characteristic is said to be fire related (Givnish 1981) in jack pine (*Pinus banksiana* Lamb.) and is probably similarly promoted in lodgepole pine. Stand disturbances which do not also lead to cone opening are therefore catastrophic for the continued growth of the latter species on a given site.

MATURITY AND COLLECTION

Seed maturity has always been taken for granted in lodgepole pine. Trees felled for cone collection have always been considered to provide more seed than required and both the seed maturity and adequacy of seed extraction have been given little notice. Seed maturation in lodgepole pine is highly dependent on altitude in the foothills of the Rocky Mountains (Hellum *et al.* 1983). It is much more important than latitude. This phenomenon may be expected to pervade the natural range of the species at ever increasing altitudes the farther south in the range.

Large commercial collections of lodgepole pine are normally made at lower altitudes and cleaned seed can be expected, therefore, to give up to 95% germination in average years. Not so for collections from subalpine, high boreal, or low alpine conditions. In 1980, all stands above 735 meters elevation in the Alberta foothills had variable amounts of immature seed by the end of September (Hellum *et al.* 1983). This seed had to enter winter dormancy in a succulent state and its survival after freezing could not be guaranteed. Seeds collected as high up as 1,400 meters in the foothills were by the end of September only able to reach 50% germination, while seeds lower down (735 m) could reach 80%. Studies are currently in progress to evaluate long-term effects of freezing at variable stages of seed maturity.

Work carried out in Scandinavia has shown that seed ripening toward the northern limits of Scots pine is also hampered by fall frosts. Simak (1966) found that seed viability could not be predicted through x-ray analysis because fall mortality occurred after full seed development, morphologically. Kardell (1973,a,b) found that immature cones could be after-ripened in cool storage if they had to be picked early because of deteriorating fall weather. Jensen *et al.* (1967) and Skre and Gjelsvik (1983) have described the chemical maturing processes in both spruce and pine, but very little is known about the physical process of maturation and what actually is damaged by fall frost.

In the seed collected in 1980 in Alberta, it was found that the cones had to have their moisture content reduced to 20%

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[2] Unpublished data. A. K. Hellum, Dep. of For. Sci., University of Alberta, Edmonton, Alta. 1979-83.

(oven dry basis) before the seeds could tolerate freezing. Cones found at 1,500 meters had nearly 60% moisture and some trees had cones with nearly 100% moisture even at the end of September, at this altitude.

The variation among trees within the stand at 1,550 meters increased at the end of September, suggesting that seeds from some genotypes mature much slower than others. Cone moisture content might therefore be a very useful criterion to use when collecting cones and seeds from lodgepole pine at higher altitudes in the foothills of the Rocky Mountains in Alberta. Adaptability to local climates at high altitudes might be selected for with ease.

Even though the issue of seed ripeness in lodgepole pine has been rated very low by operational foresters in Alberta, it is obviously a critical factor for reclamation or reforestation at higher altitudes. Seeds which are collected in immature cones should probably be handled the way Kardell (1973b) and Bates (1930) suggested. The cones should be collected before fall frosts, kept at 10°C or slightly below, stored in a humid atmosphere to avoid excessive drying of cones, and should be kept here for up to two months depending on the level of cone ripeness. More research on seed production strategy of lodgepole pine in high elevations is needed. Establishment of seed orchards at lower elevations may warrant some consideration.

HANDLING AND PROCESSING

Prescriptions for the extraction of pine seed have been written by a number of people (Bates 1930, Hellum and Pelchat 1979, Hellum and Barker 1980, Krugman and Jenkinson 1974, MacAuley 1975, Mason 1915, Rietz and Kimball 1940, Tyszkiewicz 1939 and Tyszkiewicz and Tomanek 1946). All methods prescribe the use of heat but the intensity and duration varies with species and circumstance. For lodgepole pine, a 60°C temperature is used operationally for up to 12 hours. Bonds are first "cracked open" by using much higher temperatures. In Alberta cones are exposed to about 210-230°C dry heat for up to 1.5 minutes to open the cones. This is followed by kiln tumbling at 60°C for times varying between 4 h and 12 h all depending on the serotiny of the seedlot (Hellum 1981) (Figure 3).

The bonds which hold scales together melt at temperatures above about 45°C (Cameron 1953). The actual nature of this bond is not known (Lotan 1975), but it is probably not resin. The bond cannot be broken by soaking cones in xylene, acetone or ether for hours. It seems also as if the bond may change over time because old and new cones are not equally easy to open (Hellum and Barker 1981), or to extract seeds from.

The cone should contain between 15% and 20% moisture, oven-dry basis, as it enters the kiln drum. Studies have shown

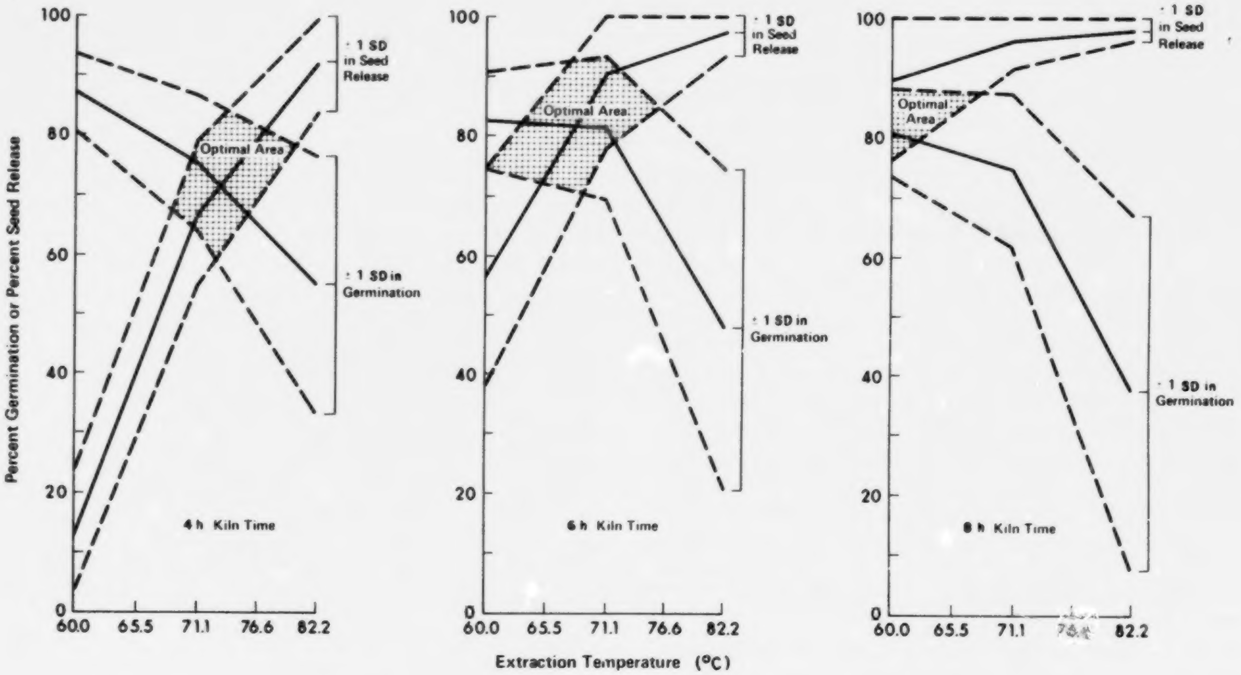

Figure 3. – Effects of temperature and time on the release and quality of lodgepole pine seed from Alberta (After Hellum and Palchat 1979).

that cone opening does not occur until cones have been dried to this level (Hellum 1981, Hellum and Barker 1980). Drier cones with less than 15% moisture release less of their seeds than when they are moister. The actual moisture level is dependent on the serotiny of the cone lot. More serotinous cones seem to require slightly more moisture to release an amount of seed equivalent to that from less serotinous cones.

A recent study (Hellum 1982) suggests further that the relative humidity in the kiln, if kept below 50%, is not as critical for seed release as is the absolute moisture content of the cone at the start of the extraction process.

The sclerenchyma tissue in the cone scales does not start to contract before the scales dry to just below 15% moisture and scales break apart without making a sound if they are wet (over 20% moisture).

Van Haverbeke (1976) showed that repeated scale flexing resulted in more seed release from Scots pine cones than just one flexure (or extraction attempt). Field observations of open cones on standing trees verify this. It is rare to find even one full seed retained in such cones.

Seed retention after one extraction process at 60°C may be as high as 30% (Hellum 1981), if the cone did not have the right moisture content when entering the kiln. This magnitude of seed loss, if applied on an operational scale, can amount to tens of thousands of dollars and may exceed the costs of more meticulous extraction efforts.

The Ideal Extraction Procedure

The ideal extraction procedure for lodgepole pine seed can only by hypothesized. It has not been developed yet. From our many studies, however, certain changes to current practices can be suggested.

The ideal approach should probably rely on removal of cone moisture by desiccation rather than heat. Cones should be "cracked open" first by using either a flash of heat (210-230°C for 1.5 minutes) or hot water (50-55°C for 5 minutes) and the cones should be monitored so that they start the kiln process with between 15% and 20% moisture contents. If cones have been dried to levels below this critical limit they will, owing to the hysteresis effect, have to be allowed to take up more water. Cones which may release most of their seeds at 15% moisture content before drying, may require up to 25% moisture to release the same amount of seed if they have been dried well below the 15% moisture content before extraction.

Cones should not be moister than 20% or seed damage from heat during extraction may result, if heat is used. Also, the higher the cone moisture content, the costiier the extraction will be. Seeds will probably be more expensive to extract from cones which have to be rewetted because they became too dry before extraction.

Because the proportion of empty seed increases over the extraction period from about 15% after the second hour to over 45% after the 12th hour (Hellum 1981), it may be necessary to terminate the extraction process sooner than seed release might indicate. Most seed is released within about 6 hours from start of kiln drying at 60°C with very little being released before the first hour of extraction, probably because the kiln is cooled initially by the cones.

The basal scales of the lodgepole pine cone contain twice as much acetone extractable material as do the tips of the cones and cone stems contain even less than the tips. As a result, basal scale flex more slowly than apical scales and may affect seed release adversely. Experience has shown that this problem varies greatly with seed lot and cannot be predicted. This phenomenon makes it doubly important to be certain that cones are allowed to take up moisture uniformly. If too dry before entering kilns, the basal scales may be a hindrance to seed extraction.

The average hectolitre of closed cones of lodgepole pine in Alberta contains between 4,000 cones (Hellum 1978) and 5,000 (Wang 1978).

SEED TESTING

In seed testing, quality is assessed by evaluating the physical and physiological characteristics of a seedlot (Bonnor 1974). The physical quality of a seedlot can be tested for its purity, weight and number of seeds per kilogram, and moisture content. The physiological quality of a seedlot can be tested for its viability, germinability or vigor. Standard testing procedures for tree seed have been developed and prescribed in the seed testing rules of the Association of Official Seed Analysts (1981) and the International Seed Testing Association (1976, 1981). As pointed out by Bonner (1974), there are two most important occasions for seed testing: first, immediately after processing, and secondly, immediately before sowing.

The viability of lodgepole pine seed can be tested by rapid methods such as tetrazolium salt staining, excised embryo test, x-ray, H_2O_2 soaking, or by simple cutting tests. These rapid techniques are time saving and were developed for testing deep dormant seed, but have been used for non-dormant seed with quick results. Thompson (1969) found the excised embryo test a useful technique for testing viability of lodgepole pine seed, while Ching and Parker (1958) effectively tested the viability of lodgepole pine seed by soaking 50 seeds in 1% H_2O_2 solution at 20°C for 5 days. For evaluating seed germinability, the most reliable method is the laboratory standard germination test. Since lodgepole pine seed is known to have varying degrees of dormancy, the standard laboratory germination test requires a double test of 4 × 100 seeds of 21 day prechilled and 4 × 100 non-prechilled seeds to be germinated on top of moist blotters at an alternating night to day temperature of 20° to 30°C with at least 8 hour light for 21 days under ISTA rules (figure

4). The AOSA (1981) rules recognize the coastal and inland varieties and require a single test of 4 × 100 seeds prechilled for 28 days and germinating them on moist blotters at 20°C to 30°C for 21 days for the inland variety and 28 days for the coastal variety.

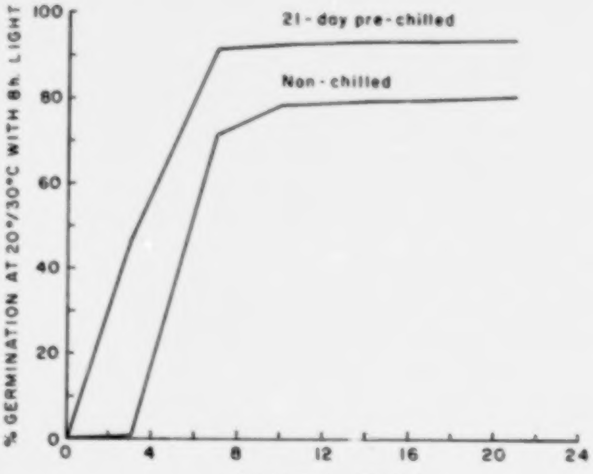

Figure 4. – A typical laboratory germination-course of a lodgepole pine seedlot from Rocky Mountain/Clear Water Forest Region of Alberta (each point represents a mean value of 56 replicates of 100 seed).

Optimum laboratory germination conditions and pretreatment for maximum germination of lodgepole pine seed have been extensively investigated by many workers (Clements 1910, Bates 1930, Haasis and Thrupp 1931, Critchfield 1957, Ackerman and Farrar 1965, Wang 1978, Kamra 1980).

Although it was suggested that optimum laboratory germination temperatures for lodgepole pine seed should correspond to the local climate of the seed origin (Haasis and Thrupp 1931), constant temperatures of 20° to 21°C (Bates 1930, Critchfield 1957) and alternating temperatures of 14° to 25°C (Bates 1930) and 20° to 30°C (ISTA 1976, AOSA 1981, Kamra 1980) are considered by their authors as near the optimum. The favourable effects produced by alternating temperature on germination are due to the apparently widened temperature range in which germination occurs (Mayer and Poljakoff-Mayber 1975). Ackerman and Farrar (1965) hypothesized a two-phase germination process in lodgepole pine seed with the first phase requiring relatively low temperatures, around 16° to 21°C, and the second phase requiring relatively high temperatures of 21° to 32°C, the two-phase temperatures overlap at 21°C which is a critical constant temperature above or below which temperature requirements for the germination process of either phase cannot be fulfilled. This hypothesis appears to be in agreement with Bates' (1930) earlier results.

Seed dormancy in lodgepole pine seed is controversial and there have been contradictory reports on the subject. Critchfield (1957) considered lodgepole pine seed to have no absolute requirement for prechilling treatment for germination, but seed prechilled for as little as 14 days will germinate faster than non-chilled seed. Germination of lodgepole pine seed from both Montana and Alberta was significantly increased by prechilling treatment, an indication of presence of seed dormancy (Thompson 1969, Wang 1980). However, both Hocking (1972) and Kamra (1980) failed to find beneficial effects of pre-chilling on germination of lodgepole pine seedlots from Alberta and B.C. It should be noted that prechilling, if done properly, will neither improve nor depress the total germination of a non-dormant seedlot unless the seedlot is damaged, weak or aged. Nevertheless, for the purpose of efficient use of seed, a double germination test in the laboratory will guarantee a satisfactory result.

Although 8 hour light is adequate for laboratory germination test of lodgepole pine seed, extended photoperiod of 16 hours can result in significant increase in germination of non-chilled seed at constant temperatures of 21° and 27°C, and alternating temperatures of 16° to 32°C (Ackerman and Farrar 1965) or 20° to 30°C (Wang 1980). However, the 16 hour photoperiod had no effect on germination of 21 day prechilled seed at 20° to 30°C (Wang 1980). Light effect does not trigger germination process of lodgepole pine until a moisture content threshold of 10 to 20% (dry weight basis) is reached (Ackerman and Farrar 1965). More research on environmental requirements for seed germination is needed to shed light on germination behavior of lodgepole pine in relation to various environments.

SEED STORAGE

The seeds of lodgepole pine are typically orthodox in that they can tolerate drying and be stored in sealed containers at sub-freezing temperatures. Under natural forest conditions lodgepole pine seed can be stored well in the serotinous cones for as long as 25 years with little loss of viability (Clements 1910). Under uncontrolled storage conditions, seeds will keep well even at ambient conditions for decades (Crossley 1955) and even centuries (Mills 1915). Although it appears that lodgepole pine seed can tolerate some haphazard storage conditions, storage to give consistent results for long-term purposes still requires rigid controls of initial seed quality, reduced seed moisture contents (4-6% of fresh weight), sealed or air-tight containers, and low storage temperatures (−15° to −18°C), under which storage life can be prolonged for 20-25 years (Cromarty *et al.* 1982, Krugman and Jenkinson 1974, Wang 1974, unpublished data[3]).

Since the keeping quality of lodgepole pine seed is closely related to the seed extracting kiln temperature (Bates 1930), further research is required to determine the effects of air and kiln drying temperatures on long-term seed storage life.

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[3] Unpublished data on file in National Tree Seed Centre, Petawawa National Forestry Institute, Chalk River, Ontario, 1983.

Further studies are also needed to examine the effect of ultralow temperatures (−150° to −196° under the vapour to liquid phase of nitrogen) on long-term preservation of genetic and physiological seed quality of lodgepole pine, as well as of other tree species (Stanwood and Bass 1982).

SEED UTILIZATION

According to a recent national statistics survey, the two major lodgepole pine growing provinces in Canada, British Columbia and Alberta, had together collected about 9000 hectolitres of cones yielding 2300 kg of seed, and used 1350 kg of seed for their reforestation in 1980-81 (unpublished data[4]). With the projected increase in the two provinces' reforestation programs from 1985 on (Johnson 1982, Luchkow 1982), large quantities of high quality seed are needed. To achieve these increasing reforestation goals, a greater effort in seed procurement and improved seed utilization will be critical. It is especially true with respect to the use of soon available genetically improved seed from seed orchards.

Stock Production

The efficient use of seed in container seedling as well as bareroot planting stock production is primarily governed by two critical factors, seed quality and pretreatment of seed.

Whereas the physical and physiological quality of seed can be controlled through standardized harvesting, handling, processing and storage, and assessed by standard laoratory germination tests, genetic quality can be controlled by recognizing and identifying different geographic sources. Very recently, it has been demonstrated that stored lodgepole pine seedlots with high percentages of filled dead seed can be effectively up-graded by recleaning with a newly developed method known as I.D.S. (Incubation-Drying-Separation) (Simak 1983).

Laboratory germination tests will provide the necessary information on germination and vigor for calculating sowing rates, degree of dormancy and appropriate pretreatments, and optimum time for sowing (Heit 1967). Since lodgepole pine seed is known to have varying degrees of dormancy among different geographic sources, only double tests or tests with and without pre-chilling treatment, will reveal those vital characteristics. According to Heit (1967), only seedlots exhibiting dormancy and high, vigorous germinability should be used for fall sowing, and the degree of dormancy will dictate the appropriate time of sowing because they will be subject to cold, harsh winter conditions. Fall-sown seed will germinate early and develop into large and healthy seedlings at reduced costs. However, fall-sown seed requires over-winter protection of the sown seed from birds and rodents. Although dormant lodgepole pine seedlots can be sown in the spring following proper prechilling treatment, nondormant seedlots should be spring-sown for maximum efficiency. Only fall-sowing of lodgepole pine seed is being practised at the Alberta Forest Service's Pine Ridge Nursery. Future seeding may be done exclusively with cold stratified seed in spring because of protection problems and higher seed efficiency.[5]

The efficient use of seed is more critical in container seedling than in nursery stock production because of the high cost and labour intensive requirements of the former. Through improved seed processing and testing facilities and technical personnel training, Pine Ridge Forest Nursery has successfully produced 100 lodgepole pine container seedlings by sowing 80 cavities with a single seed and 20 cavities with 2 seeds.[5]

It has been demonstrated that application of exogenous growth regulators, notably GA_3 and Kinetin, and other chemicals such as KNO_3 and thiourea, have been only of limited effectiveness in stimulating germination and they will not produce universal results as a substitute for prechilling treatment (Pellet 1973). The beneficial effect of prechilling is not limited to breaking dormancy, stimulating rate and total germination; but also can render the seed less sensitive to its specific temperature and light requirements. However, prechilling treatment should not be used indiscriminately, for it serves as a cold test of seed vigor and will depress germination of weak, stored seedlots (Hocking 1972). In British Columbia, prechilling treatment is applied to seedlots for nursery sowing according to laboratory germination results.[6]

For container seedling production in the United States 30-60 day prechilling is recommended only for seedlots of lodgepole pine which have been stored for a year or more (Tinus 1982). During germination period a continued moisture supply, maintenance of temperatures below optimum, and high intensity light (50% full sunlight) are also essential (Tinus 1982).

Direct Seeding

Direct seeding lodgepole pine in reforestation projects is uncommon because the seed in the slash is used instead. Site preparation (Ferdinand 1983) is usually done within a year of logging, or when the slash is brittle enough to be broken up during scarification. Only in areas of non-serotinous cones would direct seeding be a good management alternative to planting.

A recent study from British Columbia (Reid, Collins Nurseries 1983) has reiterated the pragmatic opinion of Alberta that the seed in the slash should be relied on for the regeneration of lodgepole pine. Ferdinand (1983) claims for Alberta that drag scarification after logging leads to over 90% success in meeting provincial stocking standards on cutovers of lodgepole pine within 10 years.

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[4] Canadian forest tree seed statistics: 1980-81 survey results by P. S. Janas and B. D. Haddon. Petawawa National Forestry Institute, Chalk River, Ontario, Canada 1983 (unpublished).

[5] Personal communication, L. Lafleur, Pine Ridge Forest Nursery, Smokey Lake, Alberta, 1984.

[6] Personal communication, R. Bowden-Green, B.C. Forest Service, Duncan, B.C., 1984.

Beaufait (1962) prescribed a technique by which jack pine could be regenerated by fire without running the risk of overstocking the area with seedlings. He recommended that the seed trees be left and that the slash on the ground be burnt. In this way the slash-borne seed would be destroyed and the cones on the standing seed trees would open because of the heat. This might be a useful alternative method for reestablishing lodgepole pine on cutovers where overstocking could be a serious problem (Crossley 1976a). The art is to be able to match the site preparation to the actual seed content in the slash, but this is very difficult as the numerous overstocked stands of lodgepole pine in Alberta testify. As a result, it is difficult to prescribe the ideal reforestation intensity for a given site because seed yield and seedling ingress are site dependent and influenced by heredity.

Studies in direct seeding with white spruce in Alberta (*Picea glauca* (Moench.) Voss) (Hellum 1973) show that 3 viable seed should be sown for every 30 × 30 cm area of prepared seedbed created. The same advice probably pertains to lodgepole pine and has been suggested also for Scots pine in Sweden (Hagner and Sahlen 1977). This will probably lead to stands with between 800 and 1,500 stems per hectare 10 years after harvest, judging by Alberta experience. One of the most important factors in seed use in direct seeding, as in all reforestation, is the correct seed source.

CONCLUSIONS

Seed supply is not a constraint in natural or artificial regeneration of lodgepole pine because large quantities of seed are stored in their serotinous cones. However, natural regeneration following fire or logging disturbance often results in stands that are overstocked on one hand and understocked on the other in the absence of adequate site preparation. For stands infested by bark beetle, natural regeneration could be facilitated by prescribed burning or a slash burn with seed trees left after logging.

To facilitate artificial regeneration, increased effort in seed production and seed yield, and improvement in control of seed quality and efficiency of seed utilization are essential. Seed maturity appears to be a serious problem in high elevation lodgepole pine stands and could be resolved through establishment of seed orchards on lower elevation sites or through early collection and after ripening of seed.

Since seed yield and seed quality are not affected by cone age up to 15 years, quantity of cone collection can be increased by using mechanized harvesting equipment, such as cone strippers, while quality can be controlled by sampling only certain parts of the tree crown. Physical and physiological quality of seed can also be controlled by standardized harvesting, handling, processing and storage of the seed. Research is needed to study the effect of kiln drying temperature and ultra-low temperature on the genetic and physiological quality of seed in storage. Studies on the environmental requirements for optimum germination of this species will help understand germination behavior in relation to its environments, and thus will enable foresters to prescribe appropriate cultural treatments.

Testing of seed quality, rigid controls of physical and physiological quality, as well as appropriate treatments, are all critical factors governing the improvement of seed utilization in stock production and direct seeding.

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MANAGEMENT

STRATEGIES FOR MANAGING LODGEPOLE PINE

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ABSTRACT

Lodgepole pine (*Pinus contorta* Dougl.) is an aggressive pioneer species that is well adapted to regenerating sites disturbed by fire, harvesting, or other disturbances. It is a seral species that most commonly grows in pure or nearly pure, even-aged, single-storied, overly dense stands. However, it also grows in association with a wide variety of both seral and climax species. Because of rapid juvenile growth, it overtops most of its associates for about the first 50 years.

Lodgepole pine is usually easy to regenerate naturally or artificially. It is a prolific seed producer with good crops every 1 to 3 years – serotinous and nonserotinous cones are common throughout much of its range. Serotinous cones provide abundant seed on cutover or burned areas. Nonserotinous cones can disperse enough seed to restock sites within about 60 meters (200 feet) from timber edge. Mineral soil seedbeds are best for lodgepole pine establishment and development.

Lodgepole pine is best managed using even-aged silvicultural systems – clearcutting is the most commonly used method. Seed tree cutting is not appropriate because residual trees are easily windthrown. Shelterwoods can be used where windthrow is not a problem and additional shade is needed for regeneration establishment. Group selection is the only appropriate uneven-aged cutting method, and then only where management objectives dictate the need for a variety of age classes in a relatively small area.

INTRODUCTION

Lodgepole pine – Cinderella of the West! How often have we heard that expression. Who originally coined the term? Was it a flippant or well thought-out observation? Perhaps we will never know. But we do have ample proof that the term fits and we in North America are not the only ones who think so. Forest managers in Scotland, Ireland, Iceland, and the Nordic countries also recognize the attributes of this versatile conifer. In fact, Sweden has planted lodgepole on over 200,000 hectares (500,000 acres) and it is yielding 70 percent more volume than the native species it is replacing (Hagnar, 1983).

Like Cinderella, the beauty of the species is often not recognized closest to home and it takes a Prince Charming Silviculturist from another kingdom to see its real worth. Even that jealous old stepmother, Overstocking, and ugly stepsisters – Bark Beetle and Dwarf Mistletoe – cannot forever disguise the qualities of this stepchild. Eventually, the Prince Charming Silviculturist will find the glass slipper of Management that fits Cinderella and all will live happily ever after.

Although Cinderella is a fairy tale, capitalizing on all of lodgepole pine's positive attributes and minimizing its shortcomings is a real challenge facing forest managers. The sum of all general and specific knowledge of lodgepole pine and its environs must be integrated into silvicultural prescriptions if management objectives are to be reached. This is true whether the primary objectives aim primarily at enhancing timber production, manipulating water yields, improving wildlife habitat, reducing insect and disease problems, protecting fragile sites, or combining a myriad of different uses.

Several recent lodgepole pine summary publications (Lotan and Perry, 1983; Eyre, 1980; U.S. Department of Agriculture, Forest Service, 1983a; U.S. Department of Agriculture, Forest Service, 1983b; Bunce and Bradshaw, 1983) and the previous Lodgepole Pine Symposium proceedings (Washington State University, 1975) have done much to advance the state of knowledge of the species. This paper highlights pertinent ecological and silvical characteristics of lodgepole pine and integrates them into silvicultural practices appropriate for this important forest type of the West.

ECOLOGICAL CHARACTERISTICS

Lodgepole pine is one of the most widespread conifers in the Western United States and Canada, occupying 5 million hectares (13 million acres) in the United States and over 20 million hectares (49 million acres) in Canada. This accounts for 18 percent of the commercial forest land in the Rocky Mountain area of the United States, 5 percent of the Pacific Coast area of the United States, and 22 percent of total forest land in western Canada. Together, United States and Canadian lodgepole pine forests contain over 2 billion cubic meters (73 billion cubic feet) of growing stock – an impressive number even in the 80's (Lotan and Perry, 1983).

Lodgepole pine has remarkable ecological amplitude, growing in many different environments ranging from near sea level at its northern latitudes in Canada up to 3,500 meters (11,500 feet) in Colorado. Its extensive range and wide ecological amplitude help explain the large volumes of timber described earlier.

Because of this wide range of conditions, timber production potentials range from extremely poor to very good. More than any other western conifer, it forms pure or nearly pure stands

(Eyre, 1980). That is not to say it does not grow in association with many other conifers over much of its range, particularly at the extreme upper elevations where it often joins Engelmann spruce (*Picea engelmanii* [Parry]), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), whitebark pine (*Pinus albicaulis* Engelm.), and mountain hemlock (*Tsuga mertensiana* [Bong.] Carr.) and at the lower elevations where it commonly associates with such species as Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco), western larch (*Larix occidentalis* Nutt.), ponderosa pine (*Pinus ponderosa* Laws. var. *ponderosa* and *Pinus ponderosa* var. *scopulorum* Engelm.), grand fir (*Abies grandis* [Doug.] Lindl.), and others. Although lodgepole pine does not commonly grow in mixed stands with aspen (*Populus tremuloides* Michx.), the two species are often found growing in the same general area. Lodgepole pine's ecological amplitude is also demonstrated by its presence in nearly two-thirds of the habitat types, biogeoclimatic zones, community types, site types, and forest zones classified in the Western United States and Canada (Lotan and Perry, 1983).

Throughout most of its range, lodgepole pioneers the reestablishment of conifers on sites disturbed by fire, windthrow, overgrazing, logging, or other factors. It plays more than one role in the whole successional picture. It plays a minor seral role when growing in a mixed species overstory, and in 50 to 100 years, it is usually replaced by more shade-tolerant and longer-lived species. In the dominant seral role, lodgepole pine is the principal overstory component of stands that contain a vigorous understory of shade-tolerant associates that ultimately replace it in 100 to 200 years. Repeated catastrophic fires have resulted in nearly pure stands of lodgepole pine. Here, lodgepole pine is classified as persistent seral because there is no longer a seed source for the other conifers that could grow on these sites. Although not particularly significant area-wise, lodgepole pine can be a self-perpetuating climax species where it is the only available species capable of growing in a particular environment. An edaphic factor, such as the obsidian sands of the Yellowstone National Park area, is one example that illustrates this situation.

Three highly visible factors have done much to shape the character of lodgepole pine forests – fire, mountain pine beetle (*Dendroctonus ponderosae* Hopkins), and dwarf mistletoe (*Arceuthobium americanum* Nutt. ex Engelm.). These same factors also do much in shaping the character of strategies needed for effectively managing lodgepole pine forests. Wildfire, the most spectacular of the three, has been largely eliminated with effective fire control practices for the last half century, reversing natural fire frequencies that varied from 60 to 500 years (Schmidt, 1981). Low-intensity fires were thought to be the general pattern in the Sierra Nevada (Critchfield, 1957) and high-intensity fires in the Rockies (Wellner, 1973). Recent studies, however, indicate that low-intensity fires in the Rockies may have occurred more frequently than previously thought (Arno, 1976; 1980). Recognizing that conflagrations, particularly in areas dominated by bark beetles, are still a distinct possibility, the general tone has gradually changed to one of examining the usefulness of fire in accomplishing various management activities such as site preparation and conversion of decadent stands to young, vigorous stands.

Although a number of different insects attack lodgepole pine (Lotan and Perry, 1983), mountain pine beetle is currently its most important insect pest (Amman, 1978). Historically, extensive mountain pine beetle epidemics were followed several decades later by vast stand-replacement fires. The cycle of fire, regeneration and stand development, stand maturity, mountain pine beetle mortality, and again fire is well written on the land throughout most of the lodgepole pine forest type. The following stand characteristics are associated with mountain pine beetle epidemics in natural stands (Amman, 1978): (1) trees more than 80 years of age; (2) average tree diameters over 20 cm (8 inches); (3) a substantial proportion of the trees over 30 cm (12 inches) at d.b.h. with phloem thickness of 2.5 mm (0.1 inch) or more; and (4) elevations where temperatures are optimum for brood development. Generally, stands in the Rocky Mountains with trees less than 36 cm (14 inches) d.b.h. will not support an epidemic, and trees smaller than 15 cm (6 inches) d.b.h. are not often killed (Amman and others, 1977; Cole and Amman, 1980). This varies, however, with elevation, latitude, and site. For example, mountain pine beetles are able to sustain epidemics in trees smaller than 36 cm (14 inches) d.b.h. at low elevations on good sites. As Lotan and Perry (1983) so aptly stated, "We are left with the fact that at epidemic levels, beetles are interested in exactly the same trees as forest managers."

Dwarf mistletoe is the most important disease of lodgepole pine. While affected by a number of other diseases (Krebill, 1975), dwarf mistletoe leads the list, both because of how extensive it is and because of the impacts it has on the stand (Hawksworth, 1975). Over 50 percent of the stands in the Rockies are infected to some degree, reducing height growth, seed production, stand volume, and tree vigor. Mortality rate is a function of stand age at the time of infection – the earlier the infection, the more serious the damage. Dwarf mistletoe does the most damage in those stands opened up by partial cutting, windthrow, and bark beetles. It occurs least on those stands that developed following large catastrophic fires or clearcuts where infected residual trees were not left (Alexander, 1974; Lotan and Perry, 1983).

SILVICAL CHARACTERISTICS

Silvical characteristics of lodgepole pine largely dictate the parameters of viable management options. The broader aspects, described in the classifications developed for lodgepole pine forests, encompass the most obvious silvical characteristics. Development of site-specific silvicultural prescriptions requires intimate knowledge of species characteristics. General characteristics that separate lodgepole pine from many associated conifers may either enhance or detract from its management opportunities. They include (Schmidt, 1982):

1. *Shade Tolerance*–It is very intolerant, requiring nearly full sunlight to develop properly, even though some shade during the germination period and first year of development is beneficial. Of its common associates, only western larch is more shade-intolerant.
2. *Fire Relationships*–Nearly all lodgepole pine forests owe their origin to fire. Its serotinous cones provide a ready source of seed for the highly receptive seedbed created by fires. This gives lodgepole pine a decided advantage over many of its competing associates.
3. *Site Adaptability*–Lodgepole pine is highly adaptable to combinations of different soils, climates, and topographic situations. In some cases, severe edaphic conditions, such as obsidian sands, may exclude all species other than lodgepole pine.
4. *Stand Composition*–In the persistent seral and climax successional classes, pure and near-pure stands of lodgepole pine are common, but over much of its range it grows in association with a large number of other species.
5. *Insects and Disease*–Because lodgepole pine is highly susceptible to mountain pine beetle and dwarf mistletoe–mortality due to the beetle and growth reduction due to dwarf mistletoe–both must be strongly considered in any silvicultural prescription.
6. *Seed Production and Dispersal*–
   a. Seed is produced in both serotinous and nonserotinous cones, usually within the same stand (fig. 1).
   b. Lodgepole pine is considered a prolific seeder, producing good cone crops every 2 or 3 years.
   c. Lodgepole pine seed from nonserotinous cones disperses about 30 to 60 meters (100 to 200 feet) under normal conditions. Serotinous cones disperse their seed from logging slash at or near the ground (in-place) or from cones in standing trees opened by the heat of a passing fire.
   d. Some seed is produced at an early age, even on trees under 10 years old, providing a secondary source after the initial establishment period.
7. *Seedling Establishment*–
   a. Seedlings establish best on mineral soil seedbeds, such as those produced by burning or scarifying.
   b. The combination of prolific seeding and receptive seedbeds, such as those following burns, commonly results in overstocking.
   c. Once established, lodgepole pine grows best in full sunlight and poorest where overtopped by competing vegetation.
8. *Stand Development*–
   a. Young lodgepole pine grows more rapidly than most of its associates in both diameter and height (fig. 2). Given adequate growing space, lodgepole pine equals or exceeds height growth of most of its associates for 50 years and longer.

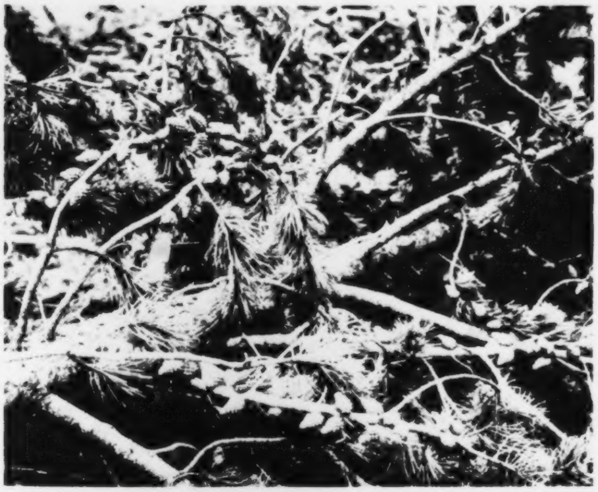

Figure 1.–Serotinous cones in lodgepole pine logging slash provide an abundant source of seed for regenerating most cutover areas, but the extent of cone serotiny should be examined before making a silvicultural prescription.

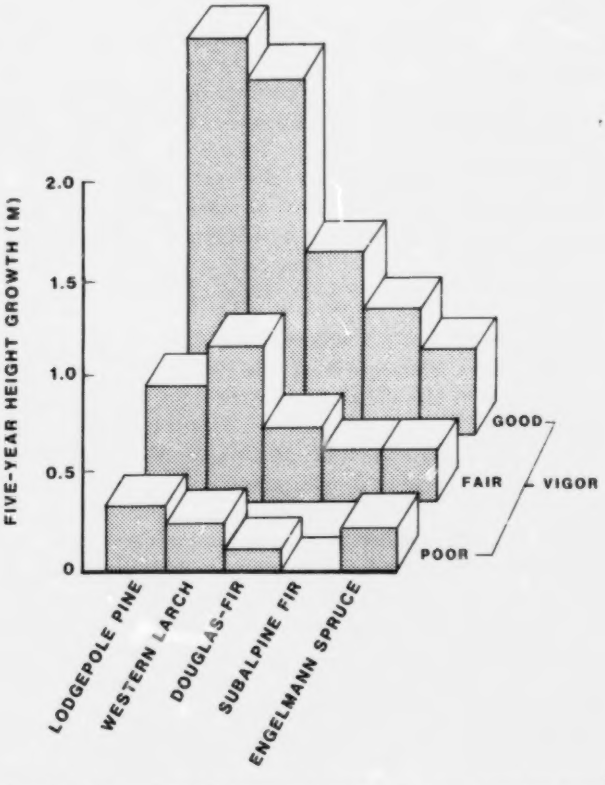

Figure 2.–A comparison of height growth of lodgepole pine and associates from age 10 to 15 (from Schmidt, 1969).

   b. If left unthinned, heavy overstocking reduces height moderately (Smithers, 1956) and diameter growth severely.
   c. On medium to good sites, cubic volume growth culminates at age 50 to 80 years and board foot volume at age 110 to 140 years.
9. *Mature Stands–*
   a. Growth in old lodgepole pine stands is normally slow or static. In many cases, net volume increment is negative due to mortality.
   b. Shallow rooting habit and closed stand characteristics make lodgepole pine in and around openings highly susceptible to wind.

The following portion of this paper deals primarily with silvicultural practices used to effect regeneration–practices which ultimately dictate long-term management of lodgepole pine forests.

REGENERATION CUTTING METHODS

Immature stands offer, by far, the greatest management opportunities in lodgepole pine forests. They have good vigor and growth potential, problems with insects and diseases are negligible, and they respond readily to cultural treatments. Because most stands in the lodgepole pine timber type are mature and overmature, they have little or no remaining growth potential. These old-growth forests contain the most saleable timber values, but offer few management opportunities except that they are the starting point for conversion to newly regenerated stands. They certainly can protect the site for soil and watershed stability, serve as wildlife habitat for some species, and provide certain esthetic qualities. Timber growth is not one of their positive attributes because net growth is usually zero–in many cases mortality exceeds growth. This section of the paper deals with converting old-growth to young growth.

Lodgepole pine is best managed with even-aged silvicultural systems, but uneven-aged management is feasible under some circumstances. Not all cutting methods under each system are applicable in every stand. Viable even-aged methods include clearcutting and shelterwood. Seed tree cutting is seldom effective because seed trees usually blow down before they have accomplished their purpose. Of the uneven-aged cutting methods–single-tree and group selection–only group selection cutting is feasible, and then only under those circumstances where management objectives include the combination of small openings and high forest, and where mountain pine beetle and dwarf mistletoe are minimal (Alexander, 1975).

Even-Aged Management

Clearcutting has been the most widely accepted regeneration cutting method in lodgepole pine forests (fig. 3). There are good reasons for this acceptance. On the vast majority of sites, this method resembles the process that nature used to convert old growth to young growth–wildfire. Clearcutting provides the best opportunities for utilization of the total wood resource, for mechanization, and for adequately preparing the site with prescribed burning or scarification for subsequent regeneration. In overmature lodgepole pine stands where mountain pine beetle, dwarf mistletoe, and risk of windthrow are high, there is little choice but to clearcut and start a new stand. Clearcutting is particularly useful in dealing with dwarf mistletoe because the source of infection is removed except around the perimeter, and the annual rate of spread is relatively low–about 0.5 m (1.5 ft) in open and 0.3 m (0.9 ft) in dense immature stands (Hawksworth, 1958). Clearcutting is also an effective tool to use against the mountain pine beetle (Cole, 1978). Small clearcuts will create a mosaic of different age and size classes in areas where probabilities of beetle attack are high. Long-term planning is absolutely necessary to assure that periodic cuts truly create an effective mosaic within a management area. In most cases, 8- to 15-hectare (20- to 40-acre) clearcuts are adequate to cope with both dwarf mistletoe and mountain pine beetle (Alexander and others, 1983). There are situations, however, where larger or smaller sizes are appropriate, particularly where stands are under attack by the beetle, or natural barriers must be reached to block the spread of dwarf mistletoe. Windthrow also has to be considered along the borders of clearcuts. Locating cutting boundaries away from topographic features that funnel winds can substantially reduce losses (Alexander, 1974). The tendency to windthrow is commonly attributed to shallow root systems, but root development varies with stand and soil conditions (Alexander and others, 1983).

Size of the clearcut is also important for considerations other than beetle and dwarf mistletoe. Where cone serotiny is high, more than adequate seeds are available in the slash for natural regeneration, so size of opening is not critical. Where the majority of trees bear mostly non-serotinous cones and natural regeneration is desired, clearcut openings should not exceed about 100 m (about 325 ft) because only about 10 to 30 percent of the seedfall at timber edge is dispersed as far as 20 m (66 ft) (fig. 4). If clearcuts must be larger, artificial regeneration will usually be needed in the area beyond effective seeding distance. Seed/seedling ratios help in making these decisions. As shown in table 1, these ratios can vary tremendously by site conditions. Because of limited seed dispersal distance and windthrow at timber edge, clearcutting in strips oriented perpendicular to the prevailing winds is often recommended (Lotan and Perry, 1983).

Shelterwood cuttings can also be used to create even-aged stands. There are problems with shelterwoods, however, such as windthrow of the reserve trees, difficulty in preparing seedbeds, potential for dwarf mistletoe dispersal to new seedlings from infected overwood, lack of growth response in the overmature reserve trees, and the eventual difficulties of removing the reserve trees without unacceptable damage to the

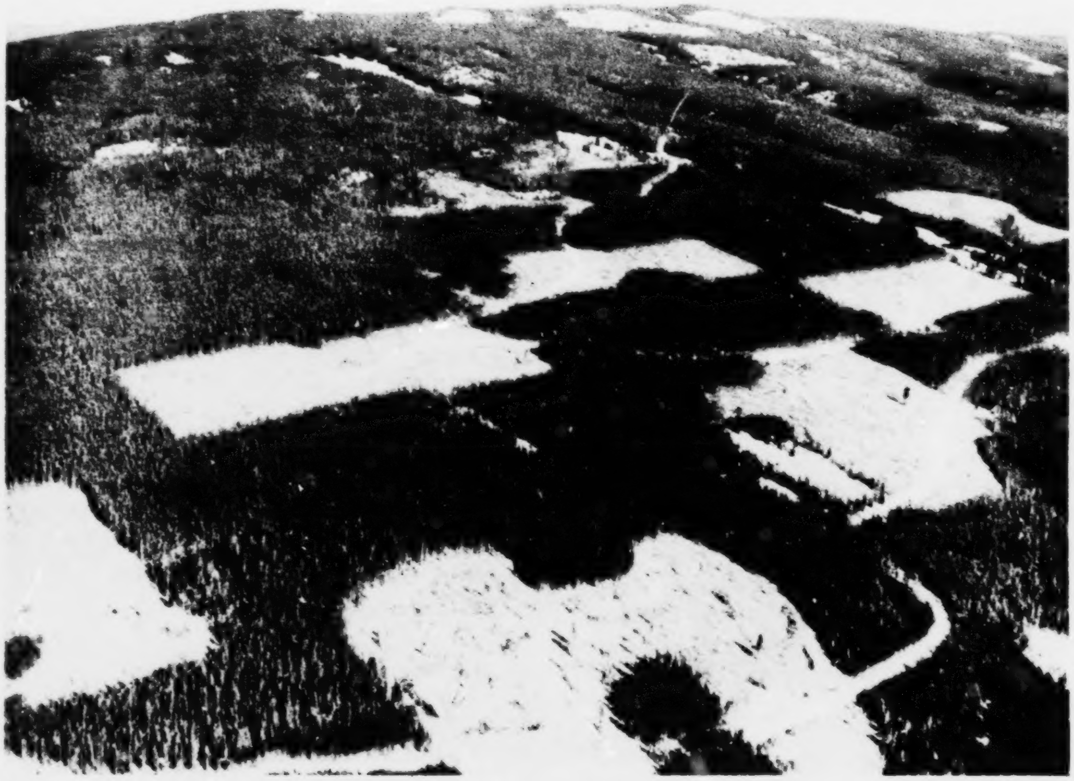

Figure 3.—Clearcutting is compatible with the silvical requirements of lodgepole pine and is the preferred regeneration cutting method in most lodgepole pine forests.

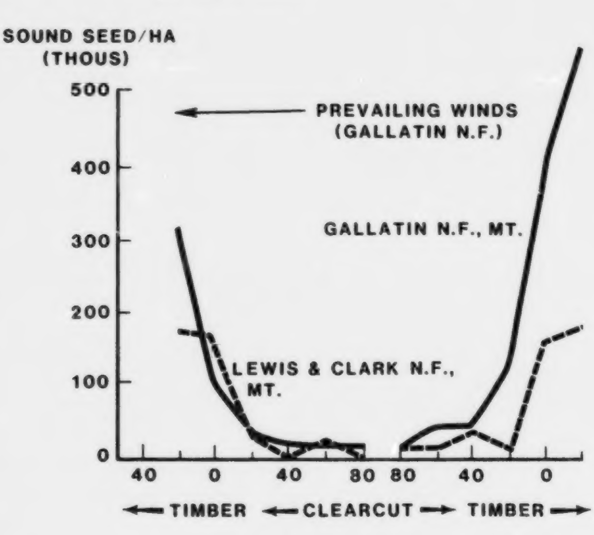

Figure 4.—Sound seed per hectare as a function of distance from the nearest timber edge (from Lotan and Perry, 1983).

newly established stand. In spite of these problems, there are situations where shelterwoods are appropriate to meet management objectives such as the need to maintain a continued forest appearance or in some cases, to provide shade for regeneration establishment on severe sites. These situations are usually applicable only in areas where timber production is not a primary concern and dwarf mistletoe infestation is minimal (Alexander, 1974; Alexander and others, 1983; Lotan and others, 1981).

Uneven-Aged Management

Uneven-aged methods have very limited utility in the management of lodgepole pine forests. "High-grading" has too long been associated with the term uneven-aged management. As a result, uneven-aged management has a worse reputation in the lodgepole pine type than it deserves. It is very difficult to match the silvical requirements of lodgepole pine with the requirements of uneven-aged management practices, particularly single-tree selection. Throwing dwarf mistletoe and mountain pine beetle into the equation complicates it even further. For example, partial cuttings to ameliorate losses to mountain pine beetle can have the same overall effect as single-tree selection.

Table 1.—Estimated final seed:seedling ratios for various site conditions in lodgepole pine forests (adapted from Lotan and Perry, 1983).

Representative site conditions	Site preparation: None or slight	Site preparation: Broadcast burning	Site preparation: Bulldozer scarification
Cool, moist, low to moderate competition	1,000:1	1,000:1	300:1
Moderate moisture and temperature, heavy competition	10,000:1	3,000:1	300:1
Cool and droughty	10,000:1	3,000:1	1,000:1
Hot and droughty (e.g., south slopes) without excessive competition	2,500:1	3,000:1	10,000:1
Hot and droughty with heavy competition	15,000:1	4,000:1	10,000:1

These practices might "beetle-proof" the stand, but in the process, leave a reserve stand with little or no growth or regeneration potential—the "cured the illness but killed the patient" syndrome (Schmidt, 1982). As a result, no viable economic alternatives are left for the manager.

Group selection offers some opportunities because the openings it creates can be large enough to allow seed dispersal, site preparation, and sufficent sunlight to accomplish the regeneration process. In many cases, these are the very type of openings and intermittent reserve stands felt necessary to sustain or enhance some wildlife populations. Those ecological situations where lodgepole pine is climax are the most likely areas for using uneven-aged management methods. Unfortunately and understandably, these are also the stands that commonly have severe dwarf mistletoe problems, which uneven-aged management tends to perpetuate.

Post-Establishment Effects of Regeneration Practices

Other authors in this symposum are dealing with growth processes, predictions, and immature stand culture. Regeneration cutting practices cannot be entirely separated from subsequent stand management because of the carryover effect that the regeneration processes may have. An obvious carryover is overstocking or understocking. Natural regeneration practices have not yet reached the refinement level needed to meet specific stocking level objectives. While no lodgepole pine stands have been intensively managed for a long period, simulations (Alexander and Edminster, 1981) indicate that regulation of stocking at an early age and periodic thinnings thereafter will substantially increase tree sizes and yields. More subtle are the initial growth differences associated with different utilization levels and site preparation methods. For example, on a Wyoming study site, lodgepole pine seedlings survived at nearly double the rate and grew much faster in height on mineral soil that had been exposed by broadcast burning or scarification than they did on areas that were covered with wood chips or had all residues removed, but little mineral soil exposed (figs. 5 and 6; Schmidt and Lotan, 1980). Similar results were observed in western larch forests,where growth differences persisted for 15 to 20 years (Schmidt and others, 1976). At this point, simulations are all we have to rely on for evaluating long-term effects of this type of influence (Cole, 1982).

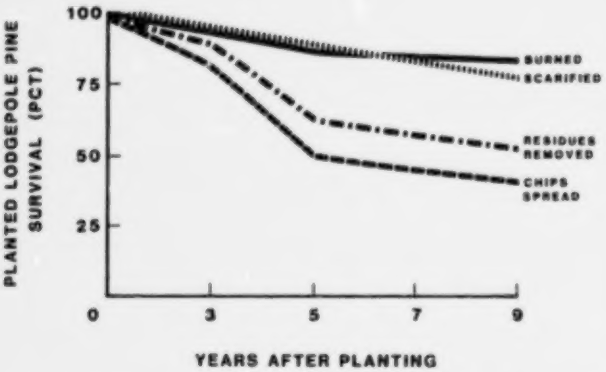

Figure 5.—Survival of planted lodgepole pine seedlings following different site prepartion methods.

Selecting the Proper Silviculture Practice

The first big question a manager faces when apprised of the biological opportunities and constraints is—what are the objectives and how can they best be met silviculturally? In many lodgepole pine forests, no single resource stands out as being vastly more important than the others. Instead, we see several resources that appear to approach equality, perhaps more so than in any other forest type of the West. Timber values are very obvious; water from these high-yielding ecosytems is becoming more and more important; wildlife such as elk (*Cervus canadensis* [Bailey]), deer (*Odocoileus* spp.), and some of

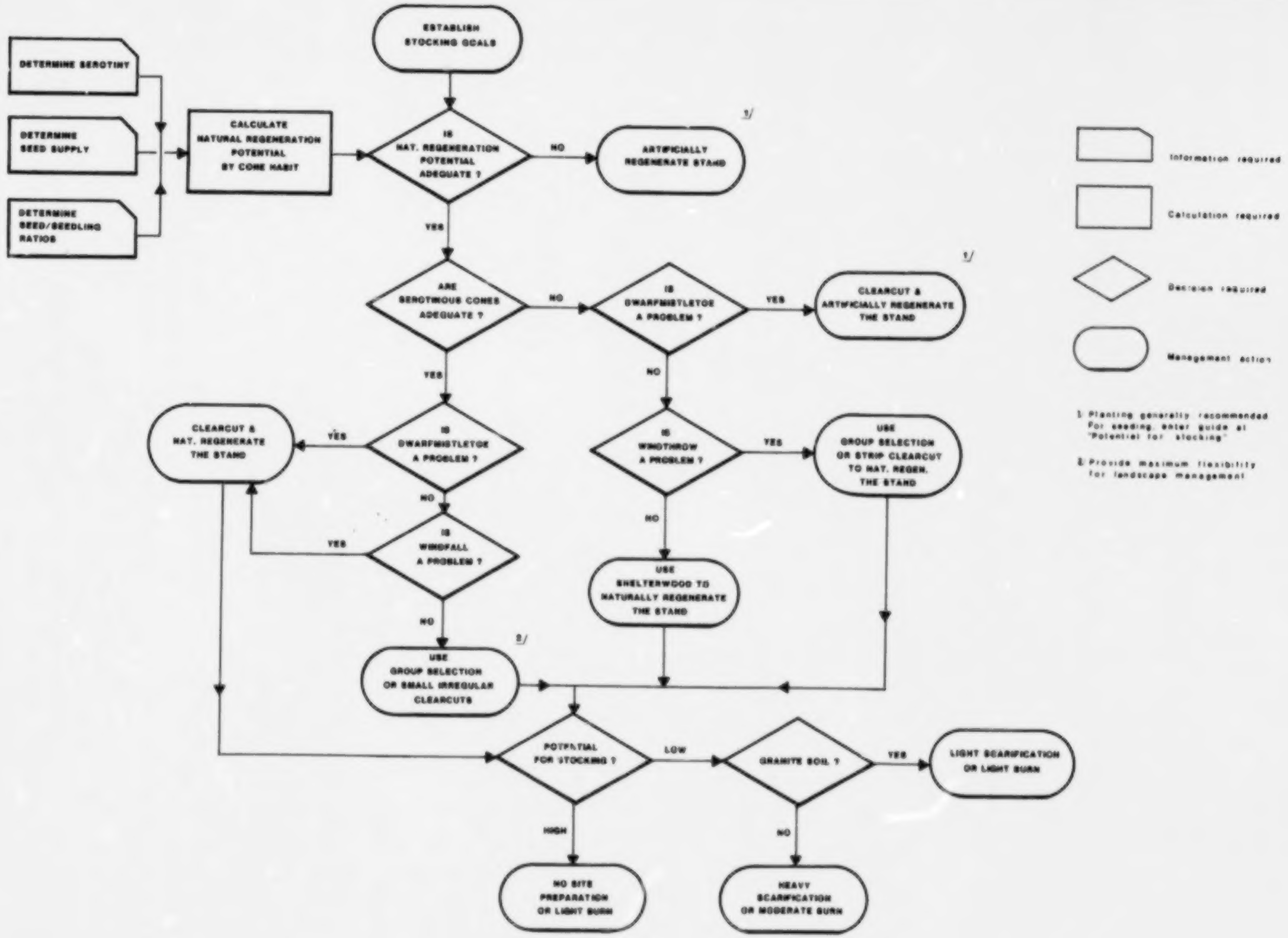
DETERMINE SEROTINY
DETERMINE SEED SUPPLY
DETERMINE SEED/SEEDLING RATIOS
CALCULATE NATURAL REGENERATION POTENTIAL BY CONE HABIT
ESTABLISH STOCKING GOALS
IS NAT. REGENERATION POTENTIAL ADEQUATE ?
NO
ARTIFICIALLY REGENERATE STAND
1/
YES
ARE SEROTINOUS CONES ADEQUATE ?
NO
IS DWARFMISTLETOE A PROBLEM ?
YES
CLEARCUT & ARTIFICIALLY REGENERATE THE STAND
1/
YES
IS DWARFMISTLETOE A PROBLEM ?
YES
CLEARCUT & NAT. REGENERATE THE STAND
NO
IS WINDFALL A PROBLEM ?
YES
NO
USE GROUP SELECTION OR SMALL IRREGULAR CLEARCUTS
2/
NO
IS WINDTHROW A PROBLEM ?
YES
USE GROUP SELECTION OR STRIP CLEARCUT TO NAT. REGEN. THE STAND
NO
USE SHELTERWOOD TO NATURALLY REGENERATE THE STAND
POTENTIAL FOR STOCKING ?
LOW
GRANITE SOIL ?
YES
LIGHT SCARIFICATION OR LIGHT BURN
NO
HEAVY SCARIFICATION OR MODERATE BURN
HIGH
NO SITE PREPARATION OR LIGHT BURN
Information required
Calculation required
Decision required
Management action
1/ Planting generally recommended For seeding, enter guide at "Potential for stocking"
2/ Provide maximum flexibility for landscape management

Figure 7.–A decision process for selecting regeneration processes in lodgepole pine forests (from Lotan and Perry, 1983).

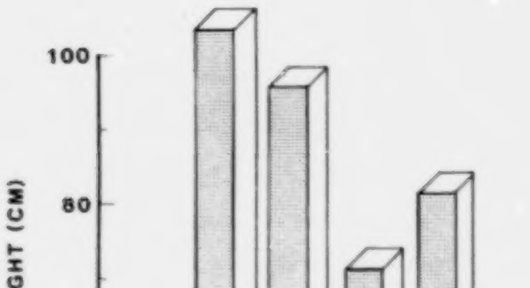

Figure 6.—Height development of planted lodgepole pine seedlings following different site preparation methods.

the endangered species such as the grizzly bear (*Ursus arctos horribilis* Ord) use these forests extensively; and transitory forage for domestic stock is locally important in many areas. All of these are affected by the selection of regeneration cutting practices and the management strategies that carry the stand through to maturity. To help in this decision-making, Lotan and Perry (1983) developed a guide that provides substantial help (fig. 7). Ultimately, however, professional judgment still plays a substantial role in making silvicultural recommendations for specific site and stand conditions. The silviculturist in the lodgepole pine type faces some of the most challenging and rewarding tasks in forests of the West.

SUMMARY

The lodgepole pine symposium in 1973 provided an in-depth look at lodgepole pine management. Since then, substantial new information has become available. In spite of that, an examination of the regeneration cutting practices suggested at that time reveals that we are prescribing essentially the same silvicultural practices today. Ten additional years of research and practice have further confirmed the utility of those recommendations and are now providing important refinement to silvicultural prescriptions. Some of the insects, diseases, and other problems associated with overmature lodgepole pine forests will only be solved when the stands can truly be placed under management. In the meantime, we must be careful that we do not prescribe quick solutions for some immediate problems that severely limit our long-term management options. Young stands hold the greatest potential for intensive management of lodgepole pine in the West.

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LODGEPOLE PINE MANAGEMENT IN SWEDEN
A STRATEGY FOR HIGHER YIELD

Stig O. A. Hagner

ABSTRACT

Small plantations of *Pinus contorta* Dougl. were established in Sweden in the 1920s. Commercial planting started at the end of the sixties. Since then more than 200,000 ha (over 500,000 acres) of lodgepole forest have been established. The plantations are of the inland variety *Pinus contorta* var. *latifolia* Engelm. from northern British Columbia and the Yukon Territory.

Pinus contorta is an interesting species from the point of view of Sweden's intensive forestry. The properties of its wood resemble those of the native pine *Pinus sylvestris* L., but it grows 60-80 percent faster. The lodgepole pine is easy to cultivate, it is hardier than the native pine in regions of severe climate, and it is more resistant to infestation. It appears to be well suited for genetic improvement.

The establishment of large-scale plantations of lodgepole pine creates a substantial timber reserve that will soon be ripe for harvesting. Rotation can be accelerated in the older parts of the existing forest, and the cut can be increased. Svenska Cellulosa Aktiebolaget (SCA) has planted 140,000 ha (350,000 acres) of lodgepole pine over a 10-year period, and this has allowed the company to increase the cut from its forests by about 300,000 m^3 (10 million cu.ft) per annum. The stand management program aims at a short rotation period of 45-60 years with little or no thinning.

Transplantation of a tree species into a new environment calls for careful scientific backup. It must be determined whether the tree can thrive and fit into its new home. For trees with a wide geographical distribution like the lodgepole pine, provenance experiments are an essential element. How well the tree withstands pathogens and other attacks can only be determined after a period of actual cultivation. The cultivation of the lodgepole pine in Sweden is an example of how the methodical introduction of an exotic species can be implemented.

INTRODUCTION

The Swedish forest industry today produces wood exclusively from native species of trees: pine (*Pinus sylvestris* L.), spruce (*Picea abies* L.), and smaller quantities of deciduous trees, mainly birch (*Betula* spp.). There is, however, a long-standing interest in experimenting with exotics, primarily conifers. Here and there one finds old plantations of introduced species, all of which have some things in common: they were established at random, they are usually small, and they do not satisfy scientific criteria for rigorous experimental design. Their originators used whatever seeds or seedlings they could get hold of, and information on provenance is scanty or lacking altogether.

Such old plantations give only limited guidance to the ability of a species of tree to survive in a new environment. One can note the survival rate, how the trees have developed, whether they have suffered damage, etc. But most trees have a wide geographical distribution. The climate of growth in their home territories varies. The results of cultivation might have been better if the choice of provenance had been different.

The Scandinavian countries lie in high northern latitudes (fig. 1). Their ability to run successful forestry industries in spite of this is due to the heating effect of the Gulf Stream. But their northerly location, which for example implies extreme daylight conditions in summertime, makes it necessary to take exotics such as the lodgepole pine from regions with a comparable climate.

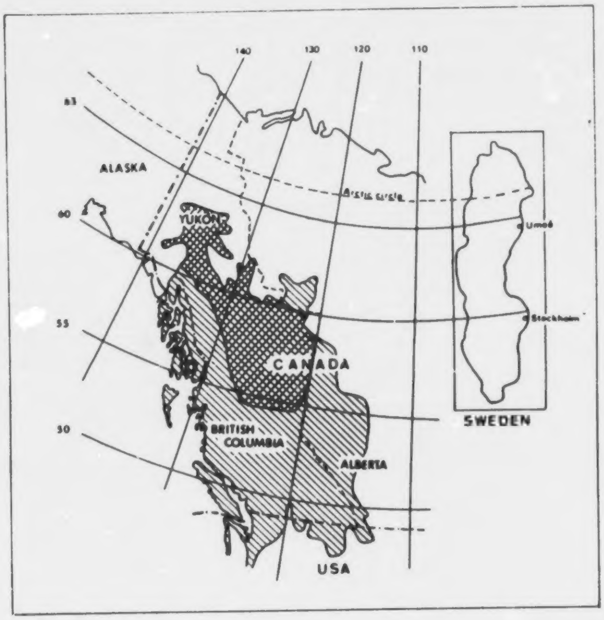


Figure 1.–Occurrence of lodgepole pine in its northern range of distribution (hatched) and latitudes in western North America and Sweden. Darker area shows location of provenances suited for North and Middle Sweden.

The first lodgepole pine plantations in Sweden were established in the 1920s, and were rather haphazard enterprises. The species was also planted in Finland at about the same time. Altogether these plantations amount to only a few hundred hectares, but they are scattered over a large number of sites. In both countries the seeds were obtained from southern and central British Columbia and adjacent parts of Alberta, which means that the variety is *Pinus contorta* var. *latifolia* Engelm. In places where the provenance happened to tolerate the climate on the new site, and where the stand was reasonably competently managed, the plantations have done well in both Sweden and Finland (fig. 2). They are now approaching an age of sixty years. On the best biotypes, the dominant trees have now reached heights of 25-28 m (80-90 feet).

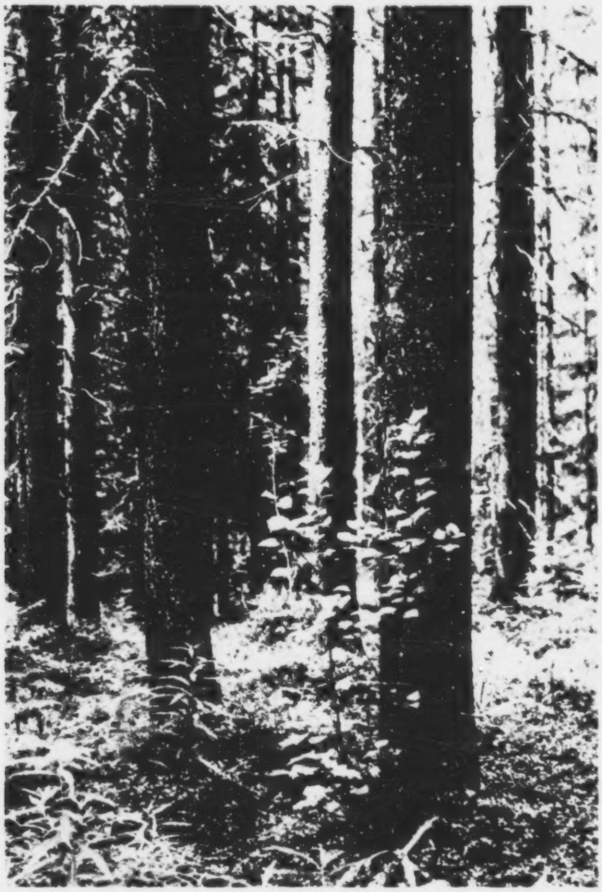


Figure 2. – 50-year-old lodgepole pine stand in southern Lapland. Latitude 64°20'. Altitude 350 m (1150 ft).

These first faltering plantation experiments were followed by a hiatus of 20 or 30 years, after which they were resumed with increasingly better scientific planning. Thus awareness gradually grew of the potential of the lodgepole pine as a species for practical forestry.

Pinus contorta has been planted commercially in Sweden since the end of the sixties. It is the only foreign species that has been introduced into Swedish forestry on a practical scale. Today there are more than 200,000 ha (about half a million acres) of lodgepole pine forest in Sweden, which makes our country the third ranking homeland of the species. The area is increasing by more than 30,000 ha (about 75,000 acres) a year with an annual plantation rate of some 70 million trees, but is still relatively small. Sweden's forests cover a total area of 23 million ha (nearly 57 million acres). But when one considers that the tree has only been cultivated seriously for fifteen years, it is clear that the newcomer has made remarkable progress.

CLIMATE, FLORA AND FORESTRY HISTORY LIKE THOSE OF NORTHERN NORTH AMERICA

The potential of cultivating lodgepole pine is mainly in northern and central Sweden (north of parallel 60°). Phytogeographically speaking, the region is part of the northern circumpolar conifer belt. The characteristics of the forest ecosystem resemble those of much of Canada and Alaska. Many, perhaps the majority, of the life-forms found there are either identical or closely related. Both flora and fauna are, however, poorer in numbers of species than their North American counterparts as a result of glaciations. We have only two commercial native conifers, *Pinus sylvestris* L. and *Picea abies* L. The latter species of spruce immigrated from the east as recently as between two to three thousand years ago.

Most of Sweden was covered with virgin forest right up until the 19th Century. Industrial exploitation began more than 150 years ago. The wood from our conifers is of good quality and was easy to sell on the international market. Times have changed, however. The forest industry had to abandon the short view of its operations and is now oriented toward a long-term sustained yield. Nowadays, it is the vitality and age makeup of the forest, together with the scope and emphasis of forest management, that determine the size and nature of the cut. In many respects, then, our forestry history resembles that of the northwestern United States and Canada. Though the process of change has advanced farther in our country, the age of exploitation is not so very far behind us. Practically all the old and middle-aged trees in Northern Sweden have origins associated with the felling of virgin forest or other events in the 19th Century.

The old phase of exploitation forestry left vast areas of creamed forest behind it. Conditions were like those that can be seen in many places in North America today. For us it has been an urgent, lengthy and laborious task to restore those areas by clear felling, soil treatment and plantation. Today, a third of the woodlands in northern Sweden consist of young forest created by such active measures. The results are encouraging. The new forest is growing much better than we had dared to hope for, and that applies to all species. It represents a welcome, vital element in our forest management planning. Highly productive new forest quickly becomes ripe for harvesting, and the period of rationing in the old forest can be shortened.

INTENSIVE FORESTRY EXPENSIVE BUT EFFICIENT

Svenska Cellulosa Aktiebolaget (SCA), the company for which I work, owns 2.1 million ha (5.2 million acres) of land in the north of Sweden. The wood from our forests is processed in our own mills to sawn timber, paper and other wood fibre products. In an integrated operation like ours, a natural interdependence grows up between primary and secondary production. To guarantee the supply of wood to the mills, the production capacity of our forests must be maintained and, if possible, increased in the long term.

This costs rather a lot of money. We cut 3 million m^3 of wood a year (over 100 million cubic feet), and every cubic meter has to bear a cost of 35 Swedish kronor (around 14 U.S. cents per cubic foot) for silviculture – soil preparation, planting, clearing, ditching, fertilization, etc. But this investment in silviculture has paid off handsomely. Over the past thirty years we have been able to increase the cut by 70 percent, and in the long term we ought to be able to double the cut compared to its present-day volume. In our high latitudes – which in terms of growth conditions can be roughly compared to average conditions in Canada – it takes a long time to get an active forest management programme rolling. But once it is rolling, its momentum in the vitalization process is tremendous.

The work of further enhancing our forest resources, then, is an important item in our long-term planning. As it brings results, we can gradually expand our logging operations; the money we spend on silviculture buys us wood from our own forests. These are the main features of our forest management strategy:

1. The older forests we have today date back to before the active management phase, and their quality if variable. In the first instance we fell old forests that are growing relatively poorly, and save the better parts for later.
2. Felled forest is replaced by new trees as soon as possible: through planting by preference, through natural regeneration as a last resort. All new stands are subject to cleaning-thinning when they have reached an average height of 2-4 m (6-13 feet).
3. We are trying to achieve a gradual reduction in the rotation period by fertilizing to accelerate tree growth and establishing new forest with good growth potential.
4. Stand treatment features few thinnings or none at all; most of the wood is harvested by clear felling.

LODGEPOLE PINE WELL SUITED TO INTENSIVE FOREST MANAGEMENT

The lodgepole pine has characteristics that make it a very attractive tree for the kind of forest outlined above.

1. The properties of its wood closely resemble those of our native pine, and to some extent those of our spruce. The saw timber is closely comparable to our own pine. The wood makes a good paper in the sulphate process, and is easily processed to newsprint.
2. The lodgepole pine evidently has an excellent assimilation apparatus. On Swedish soil it grows 60-80 percent faster, maybe in practice twice as fast, as the "best native alternative," (Hagner, 1971; Hägglund *et al.*, 1979). A lodgepole pine becomes harvestable several decades earlier than a Swedish pine or spruce on the same soil (fig. 3).

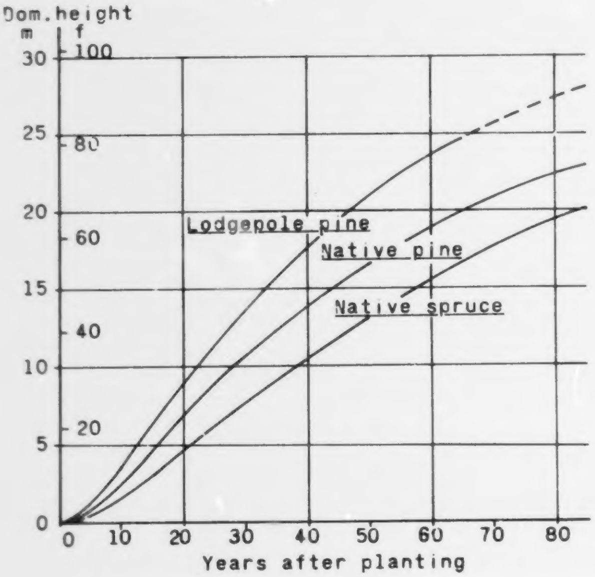


Figure 3. – Dominant height development for lodgepole pine on an average site in Middle North Sweden compared with ditto for planted native pine and native spruce.

3. It is a very good-natured tree, growing well in a broad spectrum of biotypes. In terms of increment, the lodgepole pine is the best alternative for cultivation on practically all sites of northern Sweden.
4. The lodgepole pine withstands the changeable but often cold climate of northern Sweden very well. It is hardier than the native pine at high altitudes. Its seeds ripen faster, and reach germinability at lower temperatures than the seed of Swedish pines.
5. The lodgepole pine is capable of defending its living space. It is more successful than our own conifers in competing with other aggressive vegetation on clearfelled areas.
6. It tolerates or is immune to many fungus diseases that attack the native pine. Superficial damage caused by herbivores like vole, hare, and moose, heals quickly.
7. In its large natural area of distribution the lodgepole pine has evolved strains adapted to widely varying growth conditions. It evidently possesses great genetic pliancy, and should therefore make an interesting subject for genetic improvement programmes.

8. The lodgepole pine responds very well to nitrogen fertilization (Malm, Eriksson, 1973 and 1982), (fig. 4).

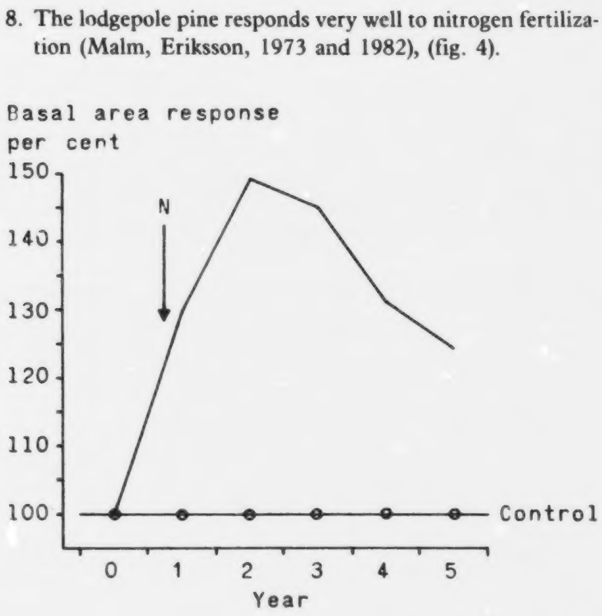


Figure 4. – Lodgepole pine responds well to N fertilizer. Average basal area response curve for three plantations, 13-17 years old, fertilized with 150 kg N ha^{-1} (134 lbs $acre^{-1}$) as ammonium nitrate.

If we sum all this up, we find we have a tree that fits well into an active forest management programme. The lodgepole pine offers us an increment that can almost be described as sensational. The uses of its wood largely coincide with those of our own conifers. It is vigorous, yet good-natured and hardy. We can get trouble-free plantations of uniformly high density with less need for corrective measures than when we plant other conifers. An intrinsically good growth rate can be made even better through fertilization and genetic improvement.

Our knowledge of what it takes to cultivate the lodgepole pine has been acquired by methodical studies over a long period of time. The lodgepole project at SCA started back in the early sixties (Hagner and Fahlroth, 1974). Ten years later we were ready to start planting on a practical scale. By that time we were confident that we knew enough about the biological prospects for cultivation in our climatically varied forest zones. We were also fairly sure what kind of growth rate we could expect from trees cultivated on Swedish soil (Hagner, 1971).

The fast-growing lodgepole pine becomes available for harvesting much sooner than if we plant native pine or spruce, so the wood supply situation improves in proportion to the rate at which we incorporate this tree into the new forests that are successively being established. SCA decided to plant 140,000 ha (346,000 acres) of lodgepole pine over a ten-year period starting in 1973. This allowed an immediate increase of 10 percent in the amount of wood cut from existing forests. The plantation programme has now been completed. We have planted a total of 300 million trees. During the same period we have cut an extra 3 million m^3 (100 million cubic feet) from our forests. This increased level of cutting, which is still being maintained, has supplied us with wood that we would otherwise have had to buy at high prices. To date, our lodgepole scheme has earned the company a profit of the order of 400 million kronor (US$ 60 million) at present-day prices.

The 140,000 ha (346,000 acres) of lodgepole pine forest now owned by SCA cover 8 percent of the company's total woodlands. Since this tree grows so fast, it will account for some 20 percent of the total increment by the year 2000. Our planted forests of native pine and spruce are doing well too, and delivering their own contribution (fig. 5). In another fifteen years the total increment for all species is expected to be 40 percent above the present level, which means that we will be able to increase the cut even more.

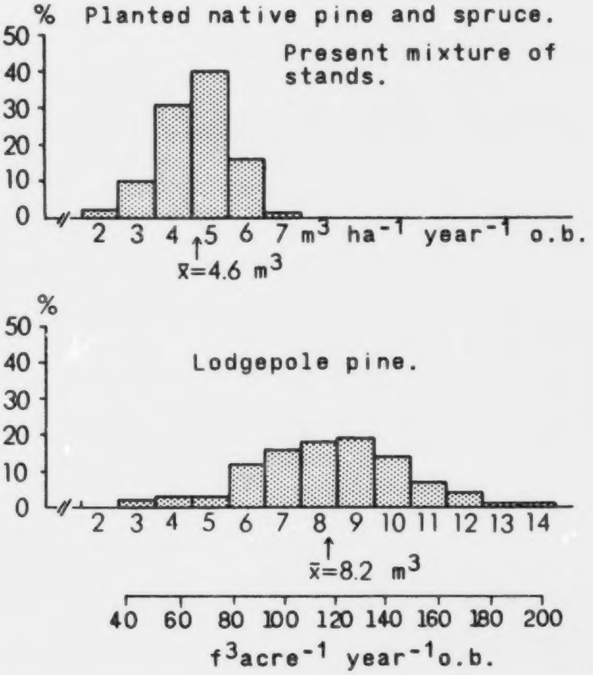


Figure 5. – Relative distribution of yield classes in Middle North Sweden for planted native pine and spruce (present mixture) and lodgepole pine planted on same sites.

Apart from a few small experimental plantations here and there, all the lodgepole pine forests in Sweden are still very young. We still lack practical experience on which to base detailed plans for forest management. Many of the older mini-plantations have developed well and are still very vigorous at an age of 50 to 60 years. Swedish production studies indicate that the average increment culminates when stands are 50 to 70 years old (Hägglund *et al.*, 1979). To come reasonably close to an optimum area yield, the trees should not be felled until they are 45 to 60 years old. This means that clear felling of lodgepole pine forests in Sweden can start some time after the year 2000.

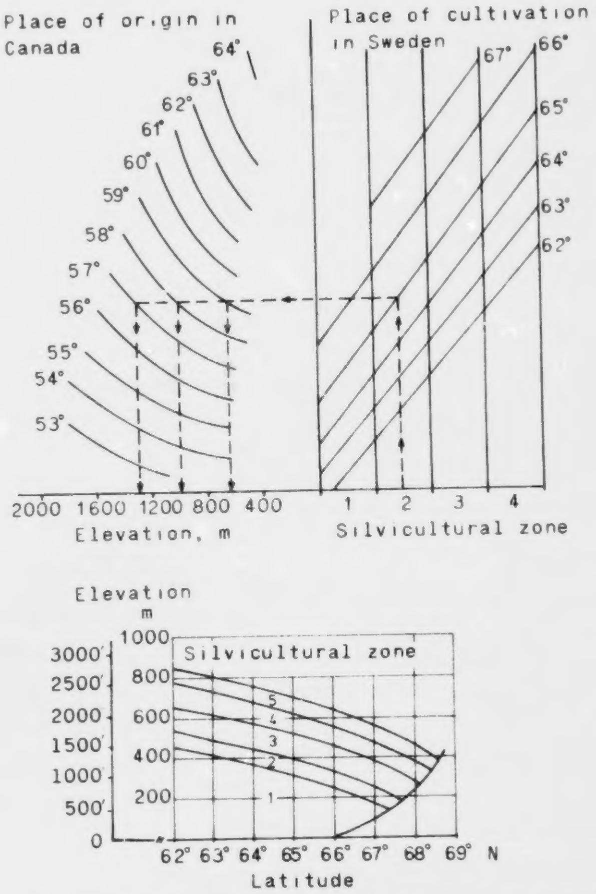
The younger lodgepole stands in Sweden normally have a density of 1,500-2,000 trees per hectare (600-800 per acre) after being cleared at the age of ten years. American studies indicate that such stands can, if desired, be allowed to grow for 50 or 60 years without any appreciable risk of growth being inhibited by overdensity (Alexander *et al.*, 1967). On the other hand, we have no systematic experimental data to guide us in the matter of thinning. However, experience to date suggests that the lodgepole pine is more sensitive than the native pine to the effects of sudden heavy thinning. The research people are currently setting up experiments that will eventually give more guidance on the question of thinning. A series of experiments has also been established for comparison of stands with densities from 600 to 8,000 planted trees per hectare (240-3,200 per acre).

INTRODUCTION THOROUGHLY PREPARED AND FOLLOWED UP

The introduction of foreign species of trees into new environments is not a new phenomenon. It has been tried in many parts of the world. The earliest plantations were usually win-or-lose ventures, and consequently their success was a matter of chance, though there are many examples of successful introductions to be found.

The introduction of the lodgepole pine into Sweden, however, was preceded by methodical preparations. In view of the country's northerly location and harsh climate, SCA recognized from the outset that the choice of provenance would be crucial. In the early sixties I personally collected lodgepole pine seeds in British Columbia and the Yukon. This, so far as I know, was the first systematic seed collection ever made in the northern part of the tree's area of distribution. The seeds were used to establish a number of widely distributed provenance experiments in northern Sweden (Hagner and Fahlroth, 1974). The results of these experiments were invaluable; they gave us guidance on the best places to obtain seeds for each individual planned plantation (fig. 6). The area in question lies in the interior of British Columbia and the Yukon Territory between the 54th and 64th parallels, i.e., up to the northern limit of *Pinus contorta* var. *latifolia* (cf. fig. 1).

Early in the proceedings we also established a large number of comparative plantations of lodgepole pine and the native *Pinus sylvestris*. Each of these side-by-side plantations comprised 20 ha (50 acres) of each species; they were distributed over a large number of sites in northern Sweden that can be continuously monitored to provide hard facts and figures on the behaviour of the lodgepole pine and its effect on our forest environment in comparison to its native counterpart. To date, the lodgepole has proved clearly superior in terms of both increment and health (Martinsson *et al.* 1983).



Example: Silvicultural zone 2, latitude 65°.
Suitable provenances: 59°, alt. 650m, or 58°, alt. 1000m, or 57°, alt. 1300m.

Figure 6. – Choice of provenance when cultivating *Pinus contorta* var. *Latifolia* in North Sweden.

At the beginning of the seventies we made a selection of premium trees in the part of the distribution area in which SCA was interested. This was done in collaboration with the forestry faculty of the University of British Columbia and the research branch of the B.C. Forest Service, and with the kind assistance of the Yukon Forest Service. Scions were selected from the trees, and some were taken to Sweden. SCA now has a total of 25 ha (63 acres) of seed orchards representing four climatic zones. By the late eighties we hope to supply a growing proportion of our seed requirements from these orchards. They are also being used by Swedish forest geneticists for progeny experiments and further genetic improvement. The B.C. Forest Service has also made grafts of the same clone material, so there should be interesting opportunities for future Swedish-Canadian collaboration in the field of genetics.

The lodgepole pine is currently the subject of a score of forestry research programmes in Sweden. The matter of pathogens is being continually monitored (Martinsson *et al.*, 1983; Karlman, 1984). Several studies have been made and are being made of the stability characteristics of the species; these can give valuable guidance for the formulation of stand management programmes (Pontén and Risby, 1981). Numerous provenance experiments are undergoing continuous evaluation (Lindgren, 1983). One interesting question is that of how far north the lodgepole pine can thrive in Sweden. Its northern limit in the Western Hemisphere lies just south of the 64th parallel. Forestry operations in Sweden extend four degrees of latitude north of that, to one and a half degrees beyond the Arctic Circle. Experience to date suggests that lodgepole pines of northerly provenance (from high altitudes in central Yukon) can thrive even there, but there are signs that this is coming close to the biological northerly limit (Lindgren and Lindgren, 1983).

RISKS CAN BE REDUCED

Where the right provenance has been chosen, the Swedish lodgepole stands are healthy (fig. 7). We have not experienced any of the epidemics of insect or fungus infestation that have hit some plantations in northern Britain. However, what happened there should serve as a warning to us. We need to ask ourselves whether it is pure chance that we have been spared, or whether any decisive factors exist that reduce or eliminate the risk in our forests.

One difference, I think, is that we were more cautious from the outset. The climate in Sweden varies a great deal with latitude and height above sea level. Experience from cultivation of our native trees has taught us the importance of matching provenances carefully to every area where we plant. That is why we based our selection of lodgepole pine provenances on exhaustive experiments. The British climate is milder, so most of the provenances used there grew well initially even if they were not climatically well adapted. Later on, however, the plantations were subjected to stress through the interaction of various growth factors, and vermin took advantage of this. It is remarkable, for example, that the insect *Panolis flammea*, which caused heavy damage to lodgepole pines in Britain, is also a member of the Swedish forest fauna but has not done any significant damage there to either native or lodgepole pines.

Naturally there are risks involved in cultivating an exotic tree, so we need to stay constantly on the alert for pathogenic organisms and learn all we can about the dangers. At present, we have the evidence of a fairly large number of lodgepole pine plantations in both Finland and Sweden, some of them up to 60 years old, to go on. Those among them that were grown from reasonably acceptable provenances are of good quality and in good health. The damage picture that they exhibit is certainly no worse than it would have been with local conifers on the same land. Without access to these old plantations it would not have been possible to assess the feasibility of the latter-day commercial plantation programme.

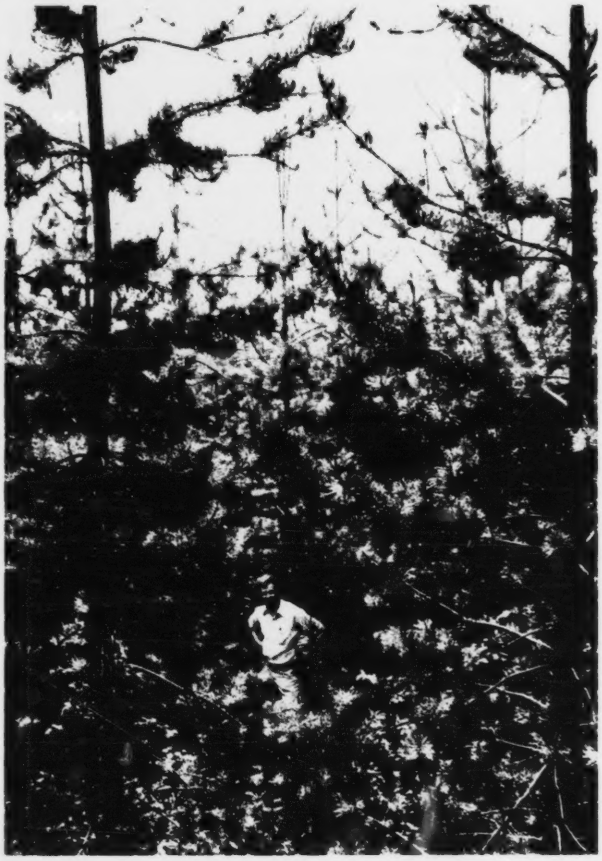


Figure 7.—15-year-old lodgepole pine plantation. Latitude 62°32'. Altitude 205 m (673 ft).

As time goes by without any signs of serious damage, the risk of anything going wrong should also progressively diminish. We already have fairly long experience of cultivation—more than 50 years. What is new about the present-day situation is that for the past fifteen years we have been planting lodgepole pines on a large scale, and the question is whether this very fact increases the risk of attack by pathogenic organisms that have hitherto been conspicuous by their absence. The possibility cannot be ruled out. Nothing of the kind has happened as yet, but we have every reason to remain alert. If nothing untoward happens in the next ten or fifteen years, I think the risk will have come down to a low level. Then, if not before, we should be able to consider the lodgepole pine a permanent and commercially valuable member of the forest flora of Sweden.

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LODGEPOLE PINE MANAGEMENT IN THE UNITED KINGDOM

Roger Lines

ABSTRACT

Conifer High Forest in Britain covers 1,375,000 hectares, all plantations except for 10,500 ha of native Scots pines. Nearly half of the Forestry Commission area is planted with Sitka spruce; lodgepole pine (12.1%) has the next largest area (101,391 ha). In Northern Ireland pure lodgepole pine covers 8% (4400 ha) of the forests. The area of lodgepole pine in British privately owned forests is 25,677 ha.

It was planted in forest trials from 1912, but on a small scale until 1947. The oldest experiment dates from 1921. Since then over 400 experiments have used lodgepole pine, including 83 provenance trials with 340 seedlots.

On fertile sites many species are more productive, so its use is confined to infertile sites, exposed uplands and sites with air pollution or salt spray. High genetic variability and use of inferior seed origins led to many management problems: instability, snow damage, slow growth, poor form, exposure damage, susceptibility to disease and pests. It was used on a wide scale in mixture with Sitka spruce in the 1950s and early 1960s. The results were often disappointing, due to incorrect choice of origin. Recently, an important nursing effect on spruce has been shown when Alaskan origins are used.

Nutritional regimes for different seed origins and site types are now quite well established. Suitable thinning regimes on sites with a low windthrow hazard are also known, though on many other sites a 'no thinning' policy is now adopted. Natural regeneration can be copious, as the serotinous habit is largely unknown under British conditions. However, pioneer crops of lodgepole pine may be replaced by more productive species in the next rotation.

INTRODUCTION

Most of the United Kingdom was covered in forest during the Climatic Optimum between the end of the Boreal and the beginning of the Atlantic Period around 3000 BC. Exploitation of forest through millenia by the relatively dense population has led eventually to the man-made landscape of today. Travelling through Britain it is rare to see a tree that has not been planted, or 'natural' vegetation which has not been affected by grazing, burning or other treatment.

The First World War resulted in massive further depletion of mature woodlands and this stimulated the creation of the Forestry Commission in 1919. Research was focused on afforestation of the 10 million ha of heathland and peatland which had a very low potential for agricultural use. The story of the early trials on these site types is described by Zehetmayr (1954, 1960) in considerable detail. It was soon discovered that lodgepole pine had good survival and its initial growth was superior to that of most other species on the poorest class of site. Lodgepole pine was first used experimentally in a high elevation trial plot planted in 1921 at Achnashellach in North West Scotland. By 1927, the need for a raised planting position on peaty areas and for phosphate fertiliser at the time of planting had been established and the following year the first provenance trials were established. In 1929 a 0.4 ha plot was planted on a deep, infertile peat bog near Fort Augustus, Inverness-shire, and this has shown the way ahead for tens of thousands of hectares of commercial planting (see p. 120 and Plate 22 in Lines, 1976).

During 1946-66 an active research programme comprising several hundred experiments was carried out with the object of extending the range of sites which could be afforested economically. These included sites at higher elevation, on more exposed, more infertile mineral soils, deeper peats and sites exposed to salt spray on the Scottish islands or to air pollution. Lodgepole pine formed an important constituent species of most of these experiments.

EARLY USE OF LODGEPOLE PINE

Lodgepole pine was introduced to Britain in 1853 by the Oregon Association from the Siskyou Mountains of Southern Oregon, a seed origin which grows poorly here. Other seed must have come from the Pacific coast, as several of the oldest specimen trees in arboreta are the fast growing subspecies *contorta* (Mitchell, 1972). Compared with other introductions made about this time from North West America (such as Douglas fir, Sitka spruce, Grand and Noble firs), growth of lodgepole pine was mediocre. David Douglas (1914) sent specimens to England in 1825, but his seeds did not germinate. Forbes (1928) in Ireland was one of the first to appreciate the wide difference between the 'coastal' and 'inland' forms when grown in the British Isles and recommended the coastal form for forest planting. With active encouragement from Mark Anderson (Anderson and Taylor, 1967) it was widely used in Eire before the Second World War, whereas it was not favoured by R. L. Robinson during his long spell as Commissioner and then Chairman of the Forestry Commission in Britain from 1919 until his death in 1952 (Macdonald, 1954).

AREA OF LODGEPOLE PINE IN THE UK

The North American forester, with his rich variety of species, may find it surprising that Britain has only one native conifer in commercial use (Scots pine). Also, that the land classed as Coniferous High Forest, which covers 1,375,000 hectares, consists entirely of plantations except for 10,500 ha which are the remnants of the ancient Caledonian Pine Forest. The distribution of species by area for Forestry Commission land is shown in Figure 1, nearly half being Sitka spruce. Lodgepole pine has the next largest area with 101,391 ha. The area of privately-owned lodgepole pine has the next largest area with 101,391 ha. The area of privately-owned lodgepole pine is 25,677 ha. In Northern Ireland, which has a separate Forest Administration, lodgepole pine covers 8% or 4400 ha of the forest area.

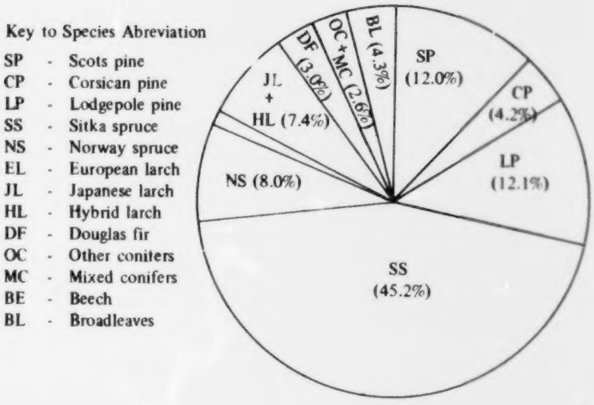

Figure 1. – Distribution, by species, of FC High Forest in Great Britain.

Although used in trials from 1912, only 1300 ha were planted before 1947 in both Forestry Commission and in private forests. The big expansion came in the early 1950s (see Figure 2 and Lines, 1976) when about 7 million trees were planted annually between 1953 and 1955.

CHOICE OF SPECIES

Choice of species has been a major concern of the forest manager in Britain for 60 years. Early foresters made strong efforts to fit the most appropriate species to different site types on an ecological basis, with secondary emphasis being given to economic factors (Forestry Commission, 1933). This approach is best illustrated by Anderson's book "The Selection of Tree Species" (1950) which quotes the ancient Chinese saying: "A gentleman takes as much trouble to discover what is right as lesser men take to discover what will pay". There are parallels with the strongly ecological emphasis in British Columbia by Krajina (1969) and Krajina, Klinka and Worrall (1982).

From the 1960s much greater emphasis was given to economic factors in both Great Britain and Northern Ireland (Johnston *et al.*, 1967). These authors also note that faced with the choice of species for a poor quality site, there is less biological and commercial risk in choosing a low production species, such as lodgepole pine, which can grow well on such a site, rather than a potentially high production species, such as Sitka spruce, which may not achieve this higher potential.

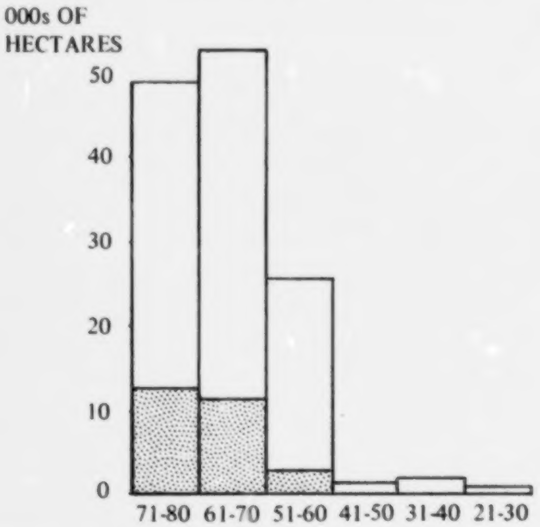

Figure 2. – Total area and private woodland area (dotted) of lodgepole pine planted in each decade in Great Britain.

Silvicultural treatments, such as chemical control of vegetation, e.g. heather, and repeated aerial application of fertilisers have more recently swung the balance in favour of Sitka spruce, as this species is much more responsive to such treatments than lodgepole pine. Views about risks from insect damage have also changed following the locally severe outbreak of Pine Beauty moth (*Panolis flammea*) on lodgepole pine in 1976 (Stoakley, 1977).

It is general policy to compare the performance of different species by calculating for each local situation the Net Discounted Revenue each species would produce. By the 1970s the potential growth rate of different species under a variety of site conditions and cultural treatments could be estimated with reasonable accuracy. Tables were prepared as a guide to local forest managers (Busby, 1974). These show that the main species choice for the Scottish uplands is nearly always either Sitka spruce or lodgepole pine.

In N. Ireland lodgepole pine is nowadays restricted to the most infertile oligotrophic peats and frost hollows which are unsuitable for the normally preferred Sitka spruce.

PROVENANCE EXPERIMENTS

In Great Britain provenance (seed origin) trials were planted on 16 sites before 1940 and on 67 sites between 1940 and 1977.

These cover a range of latitude in Britain from 50°-58° N and a wide range of soil and climatic conditions. Some 340 seedlots are included. In N. Ireland there are 25 experiments planted in 1964, 1967, 1969 and 1971. All are on peat or peaty-gley soils and they include 52 seedlots (Savill, 1976). The early results from the British trials were summarised by Macdonald (1954) and Edwards (1954, 1955). At this period, great vigour and healthy appearance of the seed origins from the Pacific coast of Washington and Oregon made them first choice for widespread use as a pioneer species on very infertile sites, many of which had a vegetation cover of heather (*Calluna vulgaris*). Knowledge of provenance variation in lodgepole pine improved as more data came from the experiments in Britain (Lines, 1966, 1976b, 1980a,b, Forestry Commission, 1968, 1969, 1970, 1971, 1972, 1976, 1977) and from Northern Ireland (Savill, 1976). Studies by Wood (1955) and Aldhous (1976) of lodgepole pine in its natural range in western North America added further information. A major advance in understanding the pattern of regional variation came from analyses of shoot terpenes (Forrest, 1980). Fundamental studies on phenology and bud development at the nursery stage gave good correlations with later growth (Cannell *et al.*, 1981). The younger experiments were assessed mainly for height, survival and early instability, the older ones also showed differences in basal area, volume, and stem form (Moss, 1971, Lines and Booth, 1972). Preliminary studies of wood properties were also carried out with thinnings from the oldest experiments (Brazier, 1980).

The latest height assessments for the series planted in 1970 comprising 24 to 81 seed origins on 12 sites are shown in Table 1. Results from the IUFRO series planted in 1972 with 24 origins on 6 sites are shown in Table 2. The two series were planned to be complementary, e.g. the 1970 series has few origins from the coast of British Columbia, but many interior seedlots, while the I.U.F.R.O. series has many from the B.C. coast and few interior sources. Results show a similar general picture, with outstanding vigour of origins from the U.S. coast from below a latitude of 47½° N. The most southerly origin from Mendocino, California (ssp. *bolanderi*) grew well on southern sites but failed in northern Scotland. A seedlot from Queets on the Pacific coast at 47½° N grew slowly and is now known to be of the same terpene group as those from west Vancouver Island (Forrest, 1980). Provenances from the Puget Sound proved rather sensitive to severe wind exposure and this accounts for the poor results at Fiunary, the most exposed site in the whole series. Some provenances from the B.C. coast

Table 1.–Heights of regional groups of origins as a % of experiment mean

	Experiment Site												
Regional group	Rumster	Glengarry	Strathardle	Mabie	Shin	Glengarry	Rosarie	Glentrool	Broxa	Rumster	Brendon	Tywi	Mean
Alaska	88.7	81.4	71.6	84.2	79.4	90.3	81.2	85.0	75.2	95.4	83.5	87.0	83.6
B.C. Coast	90.3	112.6	113.8	104.2	96.3	96.5	103.9	98.4	101.5	93.1	91.0	105.8	100.6
South Coastal	109.0	119.0	118.6	122.3	108.9	106.5	115.2	116.2	123.6	105.2	136.0	118.1	116.6
Skeena River	104.6	98.0	103.8	105.0	106.3	106.1	99.8	103.2	98.2	99.3	101.0	104.9	102.5
Bulkley River	100.2	99.6	100.8	101.0	105.2	100.2	98.6	98.3	97.9	102.9	98.4	103.0	100.5
C. Interior B.C.	100.1	89.5	97.9	93.9	106.5	97.7	95.8	96.2	95.2	98.6	95.7	95.8	96.9
S. Interior B.C.	103.0	102.4	106.9	104.1	105.6	106.6	106.5	102.9	105.8	102.6	104.8	105.4	104.7
E. of Rockies	–	–	–	77.3	–	–	83.2	–	78.2	90.8	81.9	75.5	81.2
Washington Cascades	–	–	–	82.7	74.8	76.8	82.1	–	79.9	82.6	81.2	80.6	80.1
Experiment mean height, m	2.89	3.82	3.57	4.14	3.07	3.91	3.81	4.19	3.57	2.95	2.34	3.42	

Table 2.–Heights of regional groups of origins as a % of experiment mean

	Experiment Site						
Regional group	Arecleoch	Farigaig	Fiunary	Rumster	Shin	Broxa	Mean
Alaska	82.0	79.4	107.5	89.8	80.2	73.3	85.4
N. Coast B.C.	89.0	91.3	118.0	96.4	90.4	81.4	94.4
S. Coast B.C.	107.7	111.7	99.7	109.6	105.6	113.0	107.9
Washington Coast	113.5	108.0	51.5	105.3	112.7	111.9	100.5
Oregon/Calif Coast	120.7	115.1	118.3	121.2	104.3	135.6	119.2
Yukon	57.0	51.7	41.0	50.0	–	43.9	48.7
Experiment mean height, m	3.22	2.93	1.64	3.04	3.14	3.17	

were also very vigorous, especially those from the south-east of Vancouver Island, and this contrasted with the slower growth of those from the west and northern part of Vancouver Island and the islands further north. There was also a marked variation in ability to grow well on exposed sites, such as Fiunary, where seedlots from Queen Charlotte Island were outstanding. Alaskan provenances grew slowest among the coastal group and showed their best performance on the most exposed sites.

The inland seed origins (spp. *latifolia*) showed wide variation in growth rate; the tallest group was from the southern interior of British Columbia, mainly from the hills to the south of Shuswap Lake (B.C. Seed Zone 3040). The best lots from the Skeena River are a little shorter, followed by those from the Bulkley River. Next came the group from the central interior of British Columbia and then, much less vigorous, those from Alberta, Saskatchewan and the Cascade Mts of Washington. The last show some similarity in terpene constitution with the ssp. *murrayana* from the Oregon Cascades. Finally, by far the poorest were the Yukon lots, which appear incapable of tolerating the transfer from a Boreal to an Atlantic climate, together with a latitudinal displacement of 6° S.

INSTABILITY AND SNOW DAMAGE

Prior to 1950, the methods of ground preparation used were very superficial and fertiliser input was minimal. However, improved machinery soon facilitated deeper ploughing and together with a heavier application of fertiliser and an extension onto more exposed sites, it shortly became clear that U.S. coastal seed origins now suffered greatly from early instability. This problem was not immediately apparent due to the fact that there was an unintentional switch of seed origins away from the Pacific coast of the USA. At this period only two main groups of provenances were recognised in large scale afforestation practice: 'coastal' and 'inland'. Bulk seed orders (totalling 1000 kg) for 'coastal' sources were supplied during 1949-1953 by seed merchants from the mouth of the Fraser River, particularly Lulu Island. There is no doubt that this is a 'coastal' source, but it was several yeas before it was realised that it behaved very differently from the U.S. coastal sources. In fact, it has a poor growth rate, but even more serious is its sensitivity to exposed conditions, which result in loss of foliage, dieback and generally unthrifty behavior.

Knowing the inherent vigour of the U.S. coastal sources, considerable research efforts were made to find a silvicultural solution to the problem of early stability (Neustein, 1969). The most promising technique appeared to be the use of young seedlings in polystyrene tubes (Low, 1975), though for various reasons this method of plant production has not been widely used in Britain. Later experience showed that even if early instability could be largely avoided, the dense crowns of these seed origins made them especially susceptible to wet snow damage with gale force winds in the thicket stage (8-15 years) and by the early 1970s use of U.S. coastal sources was severely restricted. Northern coastal provenances, e.g. from Queen Charlotte Islands and the west coast of Vancouver Island, B.C., were recommended as the best alternative (Lines, 1976) since these are remarkably free from this type of damage, even though they too have dense crowns.

USE OF LODGEPOLE PINE IN MIXTURES

Between 1950 and 1970 lodgepole pine was frequently planted in intimate mixtures with Sitka spruce, particularly on heather-covered peatland in Scotland and northern England, but also in N. Ireland. For example, in South Scotland these mixtures represented over one-third of the total area of about 20,000 hectares planted in 1961-1965 (Garforth, 1979). In 1950 the greater potential yield of Sitka spruce over lodgepole pine was known but the techniques for raising a spruce crop successfully on these moorlands were still uncertain. Only later was it clear that the heather competition must be eliminated either by chemical means (e.g. 2,4-D) or by shading of a tree species and a suitable fertiliser regime of phosphate, potash (and in some cases nitrogen) be applied at the correct time. There was research evidence that lodgepole pine could suppress the heather under certain conditions, whereas Sitka spruce went into 'check'.

The concept of the "insurance" mixture had a powerful influence on some forest managers. Most large moorland areas have relatively fertile patches "flushed" with minerals in the groundwater, as well as parts with thin impoverished soil. By planting a blanket mixture, it was hoped that the more demanding spruce would thrive on the fertile soils and eventually suppress the pine, whereas on the poorest ground only the less demanding pine would form a crop. On intermediate areas a mixture would form the final crop. So much for the theory – in practice it produced many problems:

1. If the provenance of lodgepole pine used was "South Coastal" it frequently suppressed the spruce as well as the heather, and because the pine was then at double the normal spacing it produced a rough-branched stand usually with basal sweep and often severe snow damage. Other common provenances grew slowly, and had thin crowns so that they did not give early heather suppression and the spruce remained in 'check'.
2. Costly tending to save the spruce was sometimes necessary.
3. It was impossible to spray the heather with 2,4-D (to which the spruce is fairly resistant) without serious damage to the pine.
4. Aerial application of fertilisers was less cost effective on mixed stands than on pure spruce stands.
5. Where a mixture will persist in unthinned stands to the end of the rotation, the timber value is likely to be less than for a single species.

Faced with treating these problem stands the forest manager has a range of options and Garforth (1979) produced an algorithm which takes into consideration the factors of each stand and the silvicultural treatments of respacing, application of fertilisers or 2,4-D and thinning.

Forestry Commission policy swung strongly against mixtures after 1970 (e.g. Davies, 1982), not only because of the difficulties experienced, but also because research trials demonstrated that more intensive fertiliser regimes and removal of heather competition by chemicals ensured adequate growth of Sitka spruce, even on sites hitherto considered too poor for spruce. However, the intensity of management and the supervisory costs are high. For example, a typical regime for Sitka spruce on an infertile site involves seven aerial applications of fertiliser during the first 18 years, plus one and often two herbicide applications at a total cost of US$650 per ha. Costs for these items for a stand of lodgepole pine would be $230 per ha because of the lower fertiliser input and no need for any herbicide.

Although it can be shown by cost/benefit analysis that this financial input pays for itself in higher timber yield of the spruce, tight financial control by central government or an increase in oil-related fertiliser prices might result in this type of regime becoming impossible to apply. Research on lower input systems using the nursing effect of other conifers on spruce was beginning to yield results by the late 1970s and this re-opened the mixture question. Experiments using Sitka spruce in mixture with Alaskan lodgepole pine (as well as with Japanese larch and with fertilisers alone) showed that these relatively slow-growing provenances, with their bushy form, not only had the effect of suppressing heather but also enhanced the growth of Sitka spruce almost as effectively as direct application of fertilisers, while nitrogen levels in the foliage were the same (McIntosh, 1983). Further trials with Alaskan lodgepole pine, Japanese larch and also *Alnus sinuata* are now in progress.

NUTRITION

Use of lodgepole pine is confined to sites of poor fertility in the UK and it was known by the 1920s that phosphate was essential on these sites. At first basic slag was used, but now rock phosphate is standard. Many trials of timing, rates and forms of phosphate showed that 375 kg/ha (50 kg/ha P) at the time of planting is best on a wide range of sites. This dose is sufficient for about 10 years when top-dressing is then considered. Foliar analysis is carried out as required by a central service as an aid to the local manager. On the poorest peatlands top-dressing with phosphate (375 kg/ha) and perhaps potash (200 kg/ha) is often required. Depending on the region and soil type, one further top-dressing may be required over the rotation. Response to nitrogen fertilisers in the early stages has seldom proved economic. Older lodgepole pine stands, if previously under-fertilized, do respond to nitrogen, though this has not become standard practice. The gross area treated with fertilizers each year in Great Britain is approximately 30,000 ha, mostly by aerial application and the bulk applied to stands of Sitka spruce. There are inherent differences in NPK levels in the foliage of different seed origins (Lines, 1970) and potash deficiencies show up much earlier in the ssp. *latifolia* than in the ssp. *contorta*.

THINNING

In the U.K. where plant spacing is usually around 2 m, it is seldom necessary to thin stands before they are 20 years old, and in recent years the poor market for small thinnings has meant that the thinning regimes shown in the Forest Management Tables (Hamilton and Christie, 1971) have been applied on an increasingly limited scale. Many upland areas are now planted with no intention of thinning throughout the rotation of 50-60 years. This has the advantage of deferring the cost of road-making until harvest time.

Light requirements of this species in N. America are discussed by Lotan and Perry (1983). In the U.K. it is regarded as less light demanding than Scots pine (Anderson, 1950).

REGENERATION

Lodgepole pine produces cones at 5-10 years in the U.K. and abundance of flowering varies with seed origin (Lines, 1977b). Copious natural regeneration occurs on sites with soil disturbance and the serotinous cone habit characteristic of ssp. *latifolia* appears largely absent here. On many sites lodgepole pine is envisaged as a pioneer crop, to be replaced in the next rotation by a more productive species.

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NUTRITION AND FERTILIZATION OF LODGEPOLE PINE

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ABSTRACT

Lodgepole pine is not considered to be a nutrient demanding species. It grows well on nutrient poor soils. A review of the relatively few fertilization trials in North America is presented. Fertilizer work in both jack pine and lodgepole pine suggests a close similarity in response between the species, which actually interbreed. Lodgepole pine appears to be particularly responsive to nitrogen additions; phosphorus deficiencies may be induced by nitrogen additions. Responses as high as 50% in volume increment over a 10-year period have been found with applications of nitrogen over 150 kg/ha. Some case study data are presented.

In North America most fertilization studies have been conducted in naturally regenerated stands on upland sites, often following spacing. Boron and copper micronutrient deficiencies have been identified on some soils. In Europe, particularly in Ireland, phosphorus and nitrogen are required in the extensive use of coastal lodgepole pine in peatland afforestation.

INTRODUCTION

Our understanding of lodgepole pine nutrition and fertilization is much better than is indicated by the sparse North American literature. This is because:

1. Lodgepole pine as a hard, two-needle pioneer pine species is apparently very similar in its nutritional requirements to other pines of this type, notably jack pine (*P. banksiana*)–with which it interbreeds naturally in Alberta–and to Scots pine (*P. sylvestris*). There is evidence to suggest that lodgepole pine will respond in the same way as these two species with regard to soil nutrient additions as fertilizer (especially nitrogen (N)) and to soil nutrient deficiencies.
2. Much work has been done in Britain, Ireland and Scandinavia on lodgepole pine nutrition and fertilization.

This paper reviews some of our understanding on these species, outlines some current studies, and presents some recent fertilization response data. Nursery nutrition of lodgepole pine will not be covered.

The species is famed for its extraordinarily wide ecological amplitude and low competitive ability. Outside of its altitudinally defined interior North American range (spp. *latifolia*), where it forms vast forests, *Pinus contorta* is "forced off" the richer sites by more competitive species and occurs on extreme sites (muskegs, dunes, rocky sites, and serpentine soils) as spp. *contorta*. In an extreme case (spp. *bolanderi*) it occurs as dwarf trees on very nutrient poor acid podzols (Critchfield 1978, 1980). Its ability to tolerate and successfully grow in extremely nutrient poor sites is borne out by mineral nutrition studies. Swan (1972a,b) found its nutritional requirements similar to Scots and slash pine (*P. elliottii*). Table 1 presents foliar nutrient concentration standards from three sources. Morrison (1974) reviewed literature on the interpretation of foliar nutrient status data. A micro-computer program using published data to provide interpretation of the nutritional status of foliage samples for macro- and microelelments has recently been developed (Ballard and Carter 1983). Color photographs of visual deficiencies in lodgepole pine are presented (Binns *et al.* 1980).

Table 1. – Published interpretations of foliar macronutrient concentrations for lodgepole pine.

	Foliar concentrations, % dry mass				
Nutrient Element	Very severely Deficient[a]	Severely Deficient	Slight to Moderate Deficiency[b]	Adequate	Source[e]
N	0.00-1.05	1.05-1.20	1.20-1.55	>1.55	I
	–[c]	–	≤1.20[d]	≥1.70[d]	II
	–	–	<1.10	≤1.40	III
P	–	0.00-0.09	0.09-0.15	>0.15	I
	–	–	≤0.07[d]	>0.17[d]	II
	–	–	<0.12	≥0.14	III
K	0.00-0.35	0.35-0.40	0.40-0.55	>0.55	I
	–	–	≤0.30[d]	≥0.60[d]	II
	–	–	<0.30	≥0.50	III
Ca	–	0.00-0.05	0.05-0.10	>0.10	I
	–		≤0.06[d]	≥0.10[d]	II
Mg	–	0.00-0.06	0.06-0.10	>0.10	I
	–	–	≤0.07[d]	≥0.09[d]	II
	–	–	(<0.03	>0.05)[f]	III

Notes:

(a) Categories are a modified version of those of Ballard and Carter (1983); data from other sources were fitted into this on the basis of associated equivalences according to the qualitative terms used by authors.

(b) For sources other than Ballard and Carter (1983), values given may also include more severe deficiencies than indicated by this category.

(c) Dash implies no explicit statement possible for the relevant categories. Please see note (b) also.

(d) Values are lower and upper limits respectively, of Swan's (1972a and b) "transition zone from deficiency to sufficiency"; includes shore pine data.

(e) Sources are as follows: I = Ballard and Carter (1983); II = Swan (1972a and b); III = Binns *et al.* 1980).

(f) Bracketed values are tentative only.

Work on nutrient cycling in the last decade has recognized two phases in stand development (Miller 1981, Royal Society 1982).

Phase I Prior to Canopy Closure

At this phase, the trees are very dependent on soil supplies and almost any nutrient may be limiting, especially when lodgepole pine is planted or occurs on extreme sites or soils. Precise and early diagnosis is clearly desirable. Lodgepole pine planted on acid impoverished mineral and organic soils in Britain and Ireland can grow with low levels of available N and potassium (K) if phosphorus (P) is applied. This characteristic of lodgepole pine has permitted the establishment of very extensive stands on oligotrophic peats in Britain and Ireland. Lodgepole pine planted on peats on the coastal belt of Norway have shown frost damage and shoot dieback due to low foliar boron concentrations (less than 3 ppm); a situation readily alleviated by borax additions to bring the concentrations up to 10 ppm. "Elimination" fertilizer trials to identify the nutrient needs of lodgepole pine planted on ombrogenous and soligenous peats have successfully yielded the appropriate fertilizer prescription, usually involving N, P, and K plus perhaps some micronutrient addition (Braekke 1977a,b). Such studies in the U.K. and Scandinavia have demonstrated dramatic growth rates for fertilized lodgepole pine with balanced nutrition. Mean annual increments of 12-15 m^3/ha/yr are attainable – values reflected in the U.K. Forestry Commission yield tables for lodgepole pine growing on good sites.

Similar dramatic response for lodgepole pine with balanced nutrition is no doubt attainable in North America, particularly for shore pine in the coastal environment. In Europe lodgepole pine is the basis for major planting programs on the poor soils made available for forestry.

Not only does lodgepole pine respond dramatically to balanced nutrition, but Scandinavian experience has shown that for unfertilized soils, it grows much faster than Scots pine. For the same level of nutrition it is apparently photosynthetically more efficient than Scots pine. Massive use has been made of lodgepole pine in Swedish planting programs (see Hagner's paper in this proceedings).

Whether or not N fertilizer will improve growth rates prior to canopy closure depends on the rates of N mineralization on the site. For peatlands, the rates are often too low to satisfy modest demands of planted trees. The plantations themselves may result in improved N-mineralization rates of peats (William *et al.* 1979). The form of added nitrogen appears to make little difference based on studies in Scotland (MacIntosh 1982) and British Columbia (B.C.). In North America, N may be limiting before canopy closure on many fire origin stands and cutover, particularly if organic matter reserves or cation exchange capacities are low in mineral soils. A key feature may be the length of the period of the flush of increased nutrient availability following fire or cutting (Assart effect). Capture of this flush by trees often occurs rapidly in fire regenerated stands with serotinous cones, but may be missed on cutovers with delayed site preparation and regeneration.

Literature on nutritional studies of this species before canopy closure is limited. A 1981 test of 17 stands of young, precommercially thinned lodgepole pine stands in the interior of B.C. used first year needle weight and graphical diagnosis of foliar analysis to screen for response to a factorial test of levels of N fertilization with and without P and K (Weetman and Four-

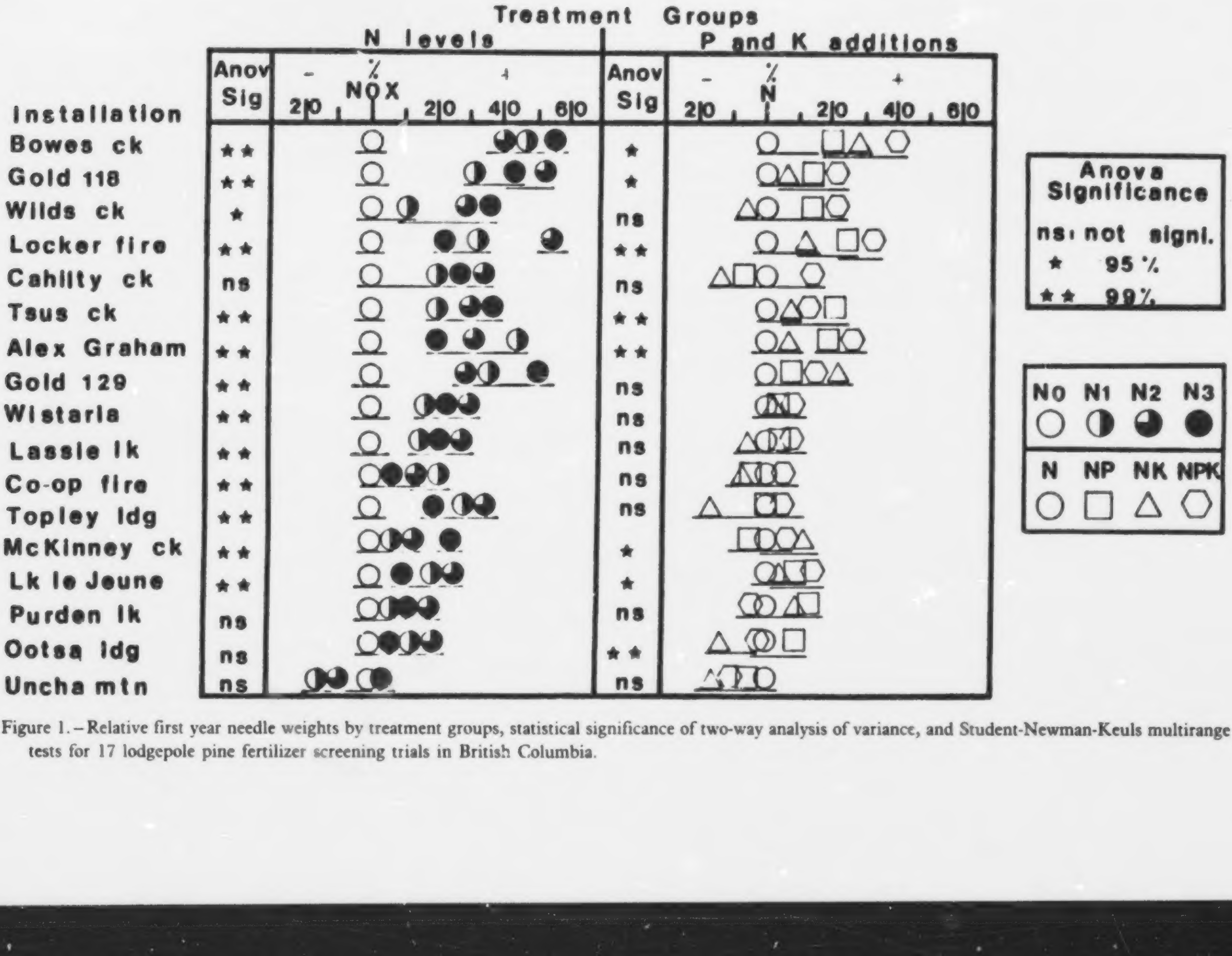

Figure 1. – Relative first year needle weights by treatment groups, statistical significance of two-way analysis of variance, and Student-Newman-Keuls multirange tests for 17 lodgepole pine fertilizer screening trials in British Columbia.

nier 1982). Over half the stands were strongly responsive, with 20% plus increases in unit foliage needle weight (Figure 1). Work with other species, notably jack pine (Weetman and Algar 1974, Camire and Bernier 1981, Timmer and Morrow 1984), has shown first year needle weight response to be highly correlated with subsequent volume response. A systematic series of 11 fertilizer trials in young lodgepole pine stands has been established by the B.C. Ministry of Forests in the interior of B.C. (Brockley 1980, 1983; see also Brockley and Barker poster session abstract). There is some evidence that N fertilization of young spaced lodgepole pine attracts more girdling by snowshoe hares and squirrels.

It may be that many young lodgepole pine stands suffer from nutrient deficiencies. Since lodgepole pine grows on such an enormous variety of sites, it is probable that on many the trees may be deficient in nutrients, almost certainly on organic soils, and probably on soils of unusual chemical composition. Nitrogen may be suspect as limiting on soils of low organic matter content. Since precommercial thinning is expensive, but often required to produce sawlog sized trees, systematic testing by foliar analysis, screening trials and conventional fertilizer trials may be warranted on stands not yet closed.

Phase II After Canopy Closure

Although before canopy closure there is a shift of nutrients from soil to tree, once the canopy is closed, the tree's demands on the soil rapidly reduces, because the cycles within the tree and through the tree-litter system are now fully charged. The cycle within the tree is based on the recovery and reuse of nutrients prior to the death of old tissues, including those of the leaf before abscission, and can be up to 85% efficient. What is discarded, except that left in heartwood, is, to a greater or lesser extent, available to roots and mycorrhizal fungi from the litter layer.

These cycles may be very tight and, when supplemented by inputs from the atmosphere in rain or from other sources, may, for elements such as K and Mg (magnesium), enable the tree to become virtually independent of soil sources of supply. For other elements, however, notably N and, to lesser extent, P, rather slow release from the decomposing litter means the tree may have to continually recharge the cycle from native soil sources. For N this immobilization in humus can lead to the development of late rotation N deficiency, a phenomenon that, because it has attracted a lot of research attention, has led to the belief that deficiency of N is the major nutritional problem in forests (Miller 1982).

This belief has been supported by the few reported fertilizer trials in closed stands, recently reviewed by Brockley (1983). These include one trial reported from Oregon (Cochran 1975, 1979), one study from B.C. (Boyd and Strand 1975), an exploratory study (Bella 1978) and a full fledged fertilization experiment in 30- and 70-year-old stands on two soil types in Alberta (Yang 1984a,b) which is presented as a case study below.

In Oregon, a single, mixed NPS treatment (N 672, P 336 and S 101 kg/ha) was compared to an unfertilized control in a thinned, 40-year-old pole-sized PL stand growing on pumice soil. Four-year and eight-year growth response was reported by Cochran (1975, 1979). Eight-year volume response averaged 18.8 m^3/ha (+79%).

Another Oregon study was established by Weyerhaeuser Co., again on volcanic soils. Treatments consisted of (1) control, (2) N at 207 kg/ha, (3) N at 414 kg/ha, and (4) N at 414, P 90, K 98 and S 78 kg/ha. The experiment was conducted on both ash and pumice soil types. Three-year volume responses as large as 12.0 m^3/ha (+87%) were reported by Cochran (1979).

In the sparse North American literature, sulfur nutrition has received notable attention. Because soils in central Oregon, the Cascade Mountains and western Alberta are reportedly low in S (Will and Youngberg 1978, Rennie 1974), S has often been added in fertilization trials of lodgepole pine (Cochran 1975, Bella 1978, Yang 1984a,b). The mechanism of S nutrition in lodgepole pine growth is not clear, although it is found that a constant ratio of 0.030 has been maintained between organic S and total N in coniferous needles (Turner 1979). Further investigations on interactions of S and N in lodgepole pine stands are needed.

The lone B.C. study was undertaken by Crown Zellerbach Corporation on TFL 9, near Kelowa. The research consisted of two parts: (1) an initial screening trial which indicated that N was the only nutrient limiting growth on the study site (Boyd *et al.* 1975, Strand and Lin 1969), and (2) a study to test the effect of N fertilization, chemical thinning, and fertilization + thinning on the growth of 40- and 80-year-old stands (Boyd and Strand 1975). N at rates of 0, 112, and 224 kg/ha as urea was applied to thinned and unthinned research plots. Thinning with MSMA was conducted at the time of fertilization. Four-year basal area growth response averaged 0.88 m^2 (+32%) and 0.28 m^2/ha (=19%) for the 40- and 80-year-old stands, respectively. Four-year volume growth response averaged 4.06 m^3/ha.

An exploratory study in Alberta (Bella 1978) in which a 70-year-old, medium site lodgepole pine stand was thinned for fence posts and then fertilized with NPS (N 112 and 673 as urea=ammonium; P 56 and 168; S 28 and 84 kg/ha) resulted in about 7 m^3/ha (30%) gain in merchantable volume over 7 years due only to N (P and S were not significant).

Closed jack pine stands have also shown a consistent response to N applications. The addition of urea (225 kg N/ha) to natural stands produced on average 8.5 m^3/ha over 5 years (Foster and Morrison 1983). It is reasonable to expect similar response in lodgepole pine. Whether or not moisture or N is the first limiting to growth in closed stands is probably a site specific phenomenon. Moisture is not a major limiting factor in most jack pine stands, but it may be in many lodgepole pine stands.

The problem of identifying and predicting response of closed stands to fertilizer additions still requires field trials; there is no sure way to identify responsive stands with confidence solely by soil analysis (such as N-mineralization rate) or foliar analysis. Screening trials using single tree fertilizer additions and foliar analysis offer a fast, inexpensive way to identify potentially reponsive stands in one growing season (Weetman and Fournier 1982). Provided lodgepole pine is rooted in mineral soil, it is probable that P and K are unlikely major limiting elements in any soil types (Bella 1978, Yang 1984a,b).

The upper limits of lodgepole pine productivity should be explored by various fertilization strategies (Axelssen 1983). There is every reason to expect that, as with Scots pine, stand productivity is directly related to N availability which in turn is controlled by N-mineralization and fertilization rates. Lodgepole pine grown close to optimum nutrition conditions should display a change in carbon allocation with increased bolewood efficiency and improved photosynthetic rate. All this suggests that the potential for growth improvement by better nutrition is obviously very great in lodgepole pine.

Case Study: Response of Lodgepole Pine to N, P, and S Fertilization in Alberta

The study areas were located southeast of Hinton, Alberta (53°25'N, 117°34'W) on the lease area of St. Regis (Alberta) Ltd. Forests here are within the Lower Foothills Section of the Boreal Forest Region (Rowe 1972). The area has a typical continental climate, characterized by long, cold winters and cool summers. The mean annual temperature is 1°C and the average frost free period is 60-65 days. Approximately 50% of the annual precipitation (530 mm) comes as snow.

Four lodgepole pine stands of age class 30 and 70 were chosen on two important soil types: Coalspur (Orthic Gray Luvisol) and Mercoal (Podzolic Gray Luvisol). Stands on these two soils were most likely to benefit from fertilization. Each study area was divided into three blocks containing 24 circular plots (0.02 ha in 70-year-old and 0.004 ha in 30-year-old stands). Nitrogen (0, 76, 188, 300, and 377 kg/ha), phosphorus (0, 38, 94, 150, and 188 kg/ha), and sulfur (0, 23, 56, 90, and 113 kg/ha) were used in a factorial experiment augmented with star design to form a second-order central composite design (Cochran and Cox 1957). Nutrients were applied in forms of urea, ammonium phosphate, triple phosphate, and elemental sulfur. Fertilizers were broadcast by using cyclone seeders in mid-May, 1972.

All plots were remeasured in early summer, 1981. In addition to plot tally of surviving trees, three dominant or codominant trees on each plot were felled and stem analysis disks were taken for assessing fertilizer effects on tree growth.

Foliar analysis of N, P, and S contents of these stands prior to fertilization is shown in Table 2. This table suggests lodgepole pine on both Coalspur and Mercoal soils were severely deficient in N, and possibly deficient in P (Table 1). Foliar S was low in comparison with those reported by Beaton *et al.* (1965) for lodgepole pine in B.C., although some of this discrepancy could be due to analytical procedures. Sulfur content in biological materials is prone to vary by the technique used.

Table 2.—Foliar N, P, and S contents prior to fertilization

	Coalspur		Mercoal	
	70-yr	30-yr	70-yr	30-yr
N%	1.10	1.07	1.09	1.15
P%	0.11	0.10	0.11	0.12
S ppm	406	452	373	439

Factorial analysis of 10-year volume increments of dominant and codominant lodgepole pine showed different response on these two soils to N, P, and S fertilization. On Coalspur soils, tree volume growth showed response only to N additions of at least 188 kg/ha (Figure 2). Phosphorus and sulfur had little effects on growth on Coalspur soils. These response patterns were observed in both the young and mature stand.

Lodgepole pine on Mercoal soils, in addition to responding to N, an addition of 56 kg/ha S also improved tree volume growth. A combination of 188 kg/ha N and 56 kg/ha S gave consistently the highest improvements in volume increments in 30- and 70-year-old stands (Figures 3 and 4). The effect of P on volume growth was not statistically significant.

Soils in western Alberta are reportedly low in S. Here, tree growth response to S occurred only on Mercoal at 56 kg/ha S level. Further studies on physiological and soil response to S application are needed to explain this phenomenon.

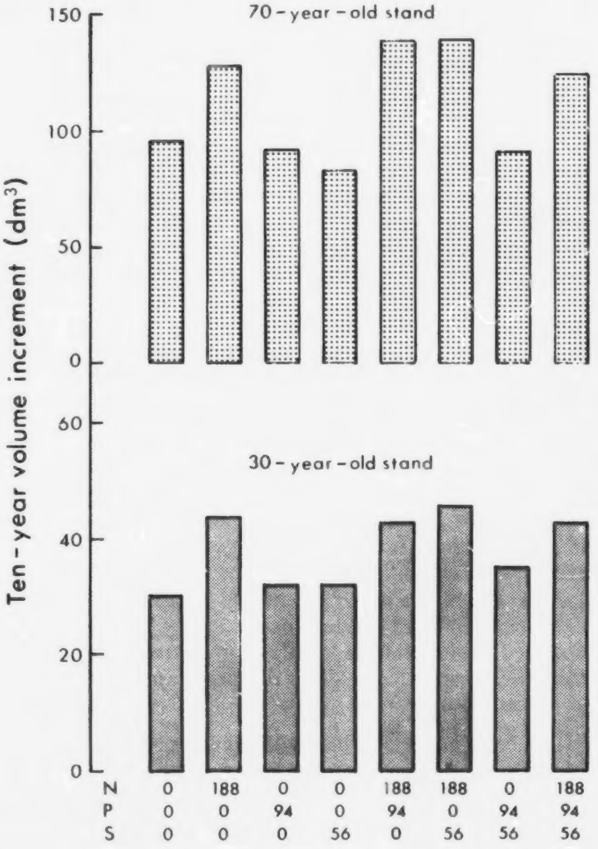

Figure 2.—Volume increments of dominant/codominant trees on Coalspur soils in response to N, P, and S fertilization.

Despite the consistent tree volume growth responses to N, P, and S application (Figures 2 and 3), net stand volume increments after fertilization were less consistent (Table 3) because of mortality. In 70-year-old stands, mortality, in number of

Table 3. Stand volume increments (m^3/ha) in 70- and 30-year-old lodgepole pine stands 10 years after fertilization.

	Coalspur			Mercoal			Coalspur		Mercoal	
Fertilizer	Initial Volume	Total Volume Incre.	Merch. Volume Incre.	Initial Volume	Total Volume Incre.	Merch. Volume Incre.	Initial Volume	Total Volume Incre.	Initial Volume	Total Volume Incre.
	70-year-old						30-year-old			
Control	246.8	65.0	68.7	304.1	55.1	58.2	123.7	38.7	116.1	45.6
N188	312.9	72.5	72.5	297.6	65.5	65.6	89.5	45.5	122.0	73.6b
P 94	251.4	68.2	72.5	279.4	53.0	52.1	97.2	31.0	110.0	53.6
S 56	292.0	58.3	60.7	237.3	64.6	62.6	97.8	30.9	122.4	56.8
N188 P 94	267.3	94.7b	92.6b	273.1	63.5	62.4	91.9	42.6	156.3	56.9
N188 S 56	259.0	64.0	65.8	232.3	62.1	58.6	83.4	44.0	89.8	47.2
P 94 S 56	284.3	71.4	70.8	273.4	65.3	67.0	100.2	49.1	104.0	38.2
N188 P 94 S 56a	273.8	81.0	82.9	275.6	70.5	70.1	93.8	48.3	101.3	58.9
N 76 P 38 S 23	287.8	58.9	60.2	240.8	70.3	70.2	79.6	37.1	99.7	61.5
N300 P 38 S 23	250.1	95.2b	96.2b	291.9	66.0	67.3	100.4	49.2	111.4	56.0
N 76 P150 S 23	279.6	68.7	72.0	298.0	71.7	75.5	93.7	39.1	83.5	42.0
N300 P150 S 23	280.7	75.8	78.6	306.2	78.0	81.7	70.7	59.2b	126.3	61.5
N 76 P 38 S 90	245.7	66.2	68.4	300.5	64.4	65.4	83.8	32.7	130.0	63.0
N300 P 38 S 90	250.3	88.9b	88.6b	271.9	66.6	65.3	85.0	47.3	112.2	72.0b
N 76 P150 S 90	202.2	78.3	82.9	286.5	61.1	59.5	98.5	51.1b	107.2	68.5
N300 P150 S 90	242.5	81.9	83.6	305.5	86.6b	85.8b	99.4	52.7b	90.8	52.6
N377 P150 S 90	281.2	99.1b	101.8b	250.0	76.2	74.6	83.7	38.2	128.9	81.9b
N300 P150 S 90	276.3	77.8	79.7	299.8	69.4	72.4	86.3	41.7	117.6	45.3
N300 P150 S113	259.8	71.4	76.7	275.0	85.2b	86.2b	71.3	28.4	91.6	43.4

a: Treatment repeated 6 times as required by the experiment design.

b: Mean significantly differs from that of the control at the 5% level.

stems per hectare, ranged from negligible (0 to 6.7%) on Coalspur to moderate (0 to 16.7%) in Mercoal stand. In 30-year-old stands, it was excessive on both soil types (Coalspur 37 to 51%; and Mercoal 32 to 48%).

In spite of mortality, in 70-year-old stands, four fertilizer combinations on the Coalspur and two on the Mercoal soils resulted in significant improvement in total as well as merchantable volume. Fertilization improved average stand productivity as much as 31 to 34 m^3/ha in total and 38 to 31 m^3/ha in merchantable volume over a 10-year period (Table 3). This means up to 50% improvement in periodic volume increment. Extrapolating stern analysis results from the 70-year-old stand showed also a volume increment of 30 m^3/ha assuming 700 dominant and codominant stems per hectare.

Although N on Coalspur soils, and N and S combinations on Mercoal soils showed significant improvement in volume increments of dominant and codominant trees in 30-year-old stands, net stand volume increments, with few exceptions, showed no significant improvement because of mortality. This suggests that in young, dense stands, thinning should precede fertilization.

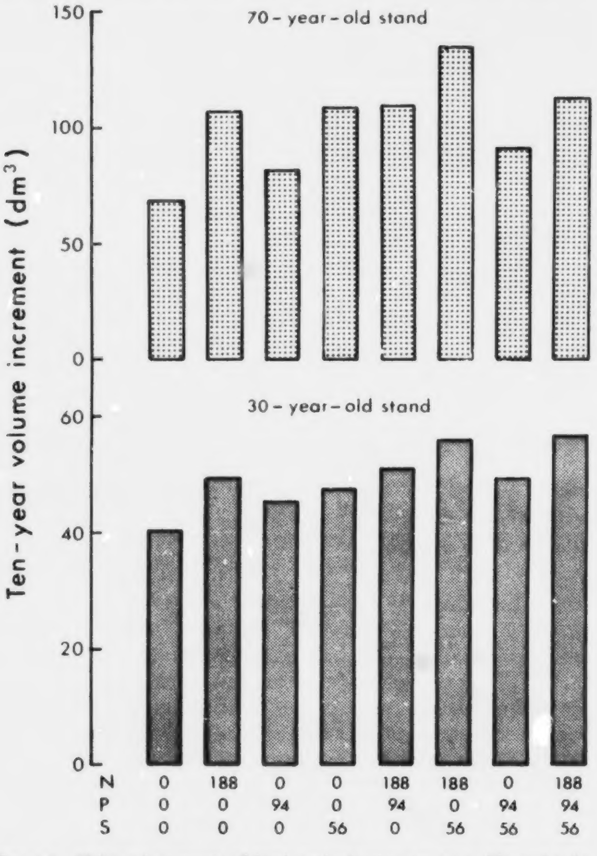

Figure 3. – Volume increments of dominant/codominant trees on Mercoal soils in response to N, P, and S fertilization.

To illustrate the potential impact of fertilization in an operational setting, we chose the McLeod Working Circle of St. Regis (Alberta) Ltd. at Hinton. This Working Circle contains 163,300 ha productive forest land just south of the mill; 48% is in the lodgepole pine cover type. Coalspur and Mercoal soils make up about 29% of the productive land area; of which about 1680 ha is in the 70-year age class of lodgepole pine. An application of N300, P150 and S90 kg/ha over this 1680 ha area could yield 36,000 m^3 merchantable volume, assuming average stand conditions on this area would be similar to those found in the study areas.

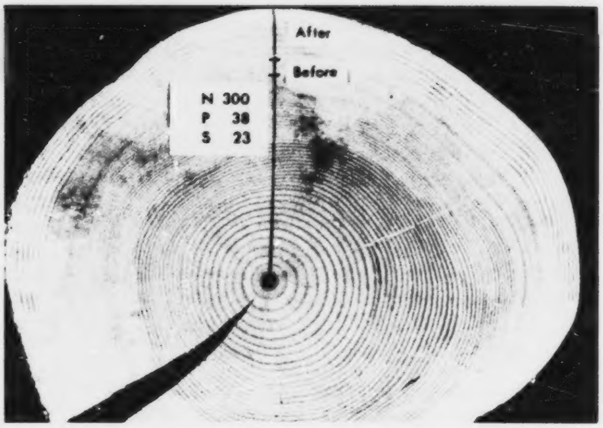

Figure 4. – Stem section showing the effect of fertilization (N300, P38, S23 kg/ha) on Dbh increment of 70-year-old lodgepole pine.

Practical Questions

1. Will nutrient removals in whole tree harvesting reduce soil fertility?
   This may occur in poor sites; particularly those low in organic matter. It is less probable on rich sites if it occurs once per long rotation.
2. Will slash burning result in fertility losses?
   There appear to be no long term nutrient balance studies on the species. Avoid organic matter loss on poor sites.
3. How should stands be tested for fertilizer response?
   There are many ways ranging from screening trials to formal factorial fertilizer/thinning experimental designs. Obtain good advice and replicate. The 1979 Forest Fertilization Conference (Gessel, Kenady and Atkinson 1979) is helpful.
4. Should lodgepole pine be fertilized at the time of planting?
   Broadcast fertilization may result in increased vegetative competition, particularly grass, for the planted trees. It may not be necessary on fresh cutovers and fires with high levels of nutrient availability. On old cuts and burns, and on poor sites low in organic matter, it may be helpful.
   Nutrient demands of planted trees are low, but nutrient supply is very dependent on the soil type. Very few trials have been done in North America.
5. Should fertilization immediately follow precommercial thinning (PCT) or be done later?
   Some current studies suggest that fertilization should follow PCT to build tree crowns.

6. Will fertilization improve insect or disease resistance?
There is some evidence that it does. Waring and Pitman (1983) found significant resistance to mountain pine beetle when canopy density was reduced and nitrogen nutrition improved. In jack pine resistance to sawfly defoliation has been found.
7. What is the best time of the year to fertilize?
The conventional time is before bud flush in the spring.
8. What is the current status of lodgepole pine fertilization?
It is entirely experimental with most of the current trials in Canada.
9. What additional studies are needed?
More cooperative screening trials and formal testing of the closed stands for response to nitrogen; identification of limiting nutrients in young stands; generation of fertilization and thinning growth response data.

CONCLUSIONS

1. Lodgepole pine can grow on sites with extremely low nutrient availability. The species has very modest nutrient demands, but responds dramatically to improved nutrient status.
2. It can be successfully established and, by use of customized fertilizer additions to achieve balanced nutrition, made to grow very quickly on poor sites, until some other factor becomes limiting.
3. The nutritional requirements and foliar analysis diagnosis values are well established.
4. Stands before crown closure, relying primarily on soil nutrition, may show deficiencies in many elements, depending on the soil type.
5. After stand closure, nitrogen deficiency can usually be suspect. Response to nitrogen additions as high as 50% in stand volume increment over a 10-year period have been found with applications of N over 150 kg/ha.

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STOCKING GUIDES FOR LODGEPOLE PINE USING THE STAND PROGNOSIS MODEL

Ralph Johnson

ABSTRACT

Conventional stand stocking guides can be constructed using forest inventories and a growth and yield model. An example stocking guide is presented for a group of forest habitat types found east of the Continental Divide in Montana. Forest inventory samples are used to establish maximum density and provide data for simulations. Results of thinning simulations are used to establish minimum stocking levels. Only even-aged sample stands are desired from the forest inventory samples. Difficulties presented by stagnation, residual overstories, and advanced reproduction are discussed.

INTRODUCTION

Stocking guides have proven useful to foresters for determining the relative stocking of stands and the need for thinning. Guides have been produced in many forms. Gingrich (1967) proposed guides showing trees per unit area vs average stand diameter and basal area per acre (fig. 1).

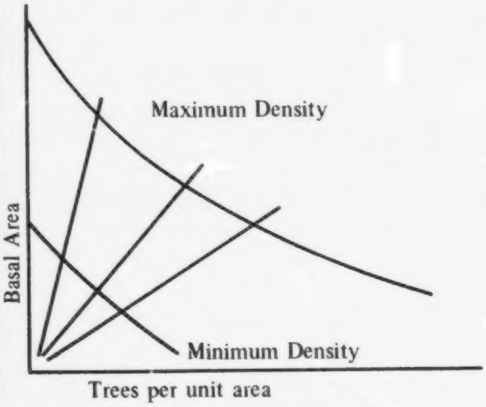

Figure 1.–An example Gingrich type stocking curve.

Basal area vs age has long been a standard shown in emperical yield table publications (fig. 2).

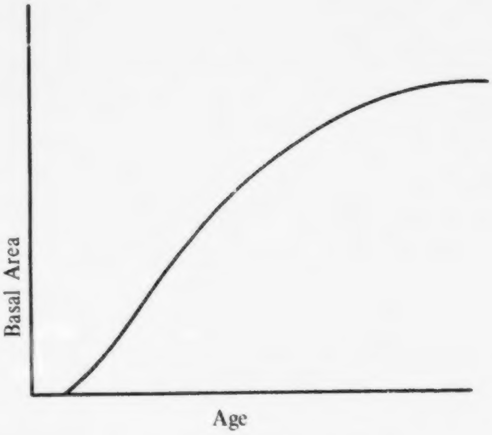

Figure 2.–An example basal area/age stocking curve.

Reineke (1933) illustrated a logarithm of trees per acre vs the logarithm of average stand diameter relationship. Such a plot is shown in figure 3.

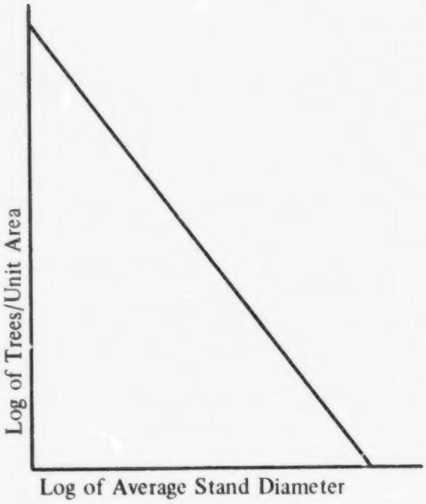

Figure 3.–An example stand density index curve.

Recently Drew and Flewelling (1979) produced stocking guides showing mean tree volume vs trees per unit area. In all of the above diagrams some form of inventory plots are usually used to establish the maximum density line on the stocking diagram. Percent stocking is related to this maximum density line. Specific percent stocking can carry management implications, such as optimum stocking or as a band defining a minimum management zone. Ernst and Knapp[1] (in press) discuss stocking guides and stocking definitions in further detail. The usual technique of establishing management lines or zones on the stocking guides is to use remeasured levels of growing stock plots.

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[1] Ernst, Richard L. and Walter Knapp. In press. Stocking standardization: concepts, terminology, and field application. USDA Forest Service, NE FES.

Growth and yield computer models can be used in lieu of stocking guides. Specific stand characteristics are simulated and the regime yielding the "best" answer is selected. Foresters may not have access to specific computer models or a narrowed range of possible alternatives may be desired to save time and computing cost. One example of computer simulation stocking yield tables are available for lodgepole pine (Myer 1967). The geographic area of applicability coincides with the area which the model applies to. In the cases of RMYLD (Edminister 1978), it is Colorado and Wyoming.

In the Northern Rockies, a variant of the Stand Prognosis Model (PROGNOSIS) is available (Stage 1973 and Wycoff *et al.* 1982). Growth and mortality functions for the model were refit for forest stands east of the Continental Divide in Montana. In this paper I will discuss how the Eastern Montana variant of the Stand Prognosis Model is being used to develop stocking guides for National Forests east of the Continental Divide in Montana. The PROGNOSIS model is an individual tree distant independent model and allows for some unique adaptations in stocking guide construction.

The following steps outline the process I used in developing stocking guides:

1. Assemble inventory information on the computer files.
2. Select even-aged stands using a computer algorithm.
3. Classify habitat types (Pfister *et al.* 1977) into groups of similar productivity.
4. Plot scattergrams of BA/Age, BA/QMD, and LN(TPA)/LN(QMD).
5. Delete stands that, after close examination, are not even-aged and delete stands thought to be stagnated.
6. Hand draw maximum curves on the scattergrams.
7. Fit mathematical functions of hand fit maximum curves.
8. Incorporate the mathematical functions of the maximum curves in the PROGNOSIS.
9. Select sample stands near the maximum line.
10. Simulate a range of management alternatives for the selected stands.
11. Select the alternative that has the minimum stocking level and still meets the management objectives.
12. Plot the minimum points from each of the simulations that were selected.

The maximum stocking line is that level biologically possible for the particular habitat type group. This does not indicate a level one would necessarily want to maintain a stand at. Setting minimum lines, the lowest stocking level a stand would be kept at, first requires defining the management objectives for the land. I defined the management objective as merchantable fiber production. The USDA Forest Service merchantability standards for the forests east of the Continental Divide in Montana was input in the PROGNOSIS model. A list of sample locations falling close to a maximum line (discussed later) was produced along with the general stand characteristics of location, age, basal area, trees per acre, and average stand diameter. Typically there were more samples than could be handled, so a subsample of locations and ages was selected.

Each subsample was simulated using the Eastern Montana variant of PROGNOSIS, first with no thinning. Taking into account the likelihood of mountain pine beetle epidemics into the general age of culmination of mean annual increment, 90 years was the assigned rotation age for this example. The PROGNOSIS model with its mountain pine beetle extension (Crookston *et al.* 1978) allows the flexibility to let each sample stand have its own rotation age, and this was done for some habitat groups. For the example habitat group 6, one rotation age of 90 was used.

SCREENING THE EVEN-AGE DATA INTO GROUPS OF HABITATS WITH SIMILAR PRODUCTIVITY

Several silviculturalists with field experience in timber stands east of the Continental Divide were asked to consolidate the 100 plus habitat types shown in Pfister into groups that had similar productivity. Eleven such groups were identified for eastern Montana. The group I will refer to in this paper is Eastern Montana Habitat Group 6, an aggregate of the following 10 habitats:

PSME/VACA	Douglas-fir/dwarf huckleberry
PSME/LIBO-SYAL	Douglas-fir/twinflower-snowberry
PSME/LIBO-CARU	Douglas-fir/twinflower-pinegrass
PSME/LIBO-VAGL	Douglas-fir/twinflower-blue huckleberry
PICEA/LIBO	Engelmann spruce/twinflower
PICEA/SMST	Engelmann spruce/starry solomon's seal
ABLA/LIBO-LIBO	Subalpine fir/twinflower-twinflower
ABLO/LIBO-XETE	Subalpine fir/twinflower-beargrass
ABLA/LIBO-VASC	Subalpine fir/twinflower-Grouse whortleberry
PICO/LIBO	Lodgepole pine/twinflower

A computer algorithm sorted the large collection of inventory samples for just those in specified habitat types and "appeared" to be even-aged (e.g., the difference in age between the oldest and youngest tree did not exceed 35 years or a specified percent of rotation age). As might be expected, some plots showed as being young even-aged; the big old trees were cull and age was not obtainable from increment cores or there were seedlings which did not have an age recorded. Later in the process, our crew of silviculturists looked at the PROGNOSIS Stand Composition Table to remove those stands that obviously were uneven-aged based on their diameter distributions. Figure 4 shows an example of one that is likely to be uneven-aged. Failure to remove uneven-aged stands will result in biased basal area vs age plots. My experience leads me to the conclusion that the curves will tend to be skewed to the left, indicating more basal area at younger ages than could actually exist.

FINDING THE MAXIMUM STOCKING LINES

Scattergrams of basal area/age, basal area/average stand diameter, and log (trees per unit area/)log (average stand diameter)

Stand composition

Year	Stand Attribute	Percentile points in the Distribution of stand attributes by D.B.H.						Total/acre of stand attribute
		10	30	50	70	90	100	
		(D.B.H. in inches)						
1981	Trees	.1	.1	.1	.1	8.5	17.1	1629. Trees
	Volume:							
	Total	6.6	8.2	9.9	11.0	14.3	17.1	4187. CuFt
	Merch	6.9	8.5	9.9	11.0	14.3	17.1	3657. CuFt
	Merch	7.2	8.7	10.9	11.6	15.4	17.1	12485. BdFt

Figure 4.—A portion of a PROGNOSIS Stand Composition output used to screen multistoried or likely uneven-aged.

provided the base for locating the maximum density line. The maximum line was hand placed and, as is illustrated in figs. 5 and 6, did not strictly go through the maximum points. Note that there is a well defined maximum zone. This line has been referred to as the average maximum density in what appears on the surface to be contradictory terminology.

After functionalizing the maximum line, the function was incorporated into the Eastern Montana variant of PROGNOSIS. I incorporated the maximum basal area as a function of age, but I could have just as easily used the maximum basal area vs average stand diameter line. In PROGNOSIS, the maximum basal area function overrides the basal area maximum embedded in the PROGNOSIS model code. Because the embedded PROGNOSIS basal area maxima are for a large collection of forests, and are by definition the maxima, the stocking guide derived maxima for subsets of the base model tend to be lower.

SETTING THE MINIMUM STOCKING LINE

The minimum line was defined as the stocking level producing the same merchantable volume at rotation age as the unthinned stand would produce at rotation age. It is possible under this definition and the stands' management direction for a lower stocking level, to produce more volume over the rotation when intermediate harvest volume is included. That would redefine my definition of the minimum line.

For each subsampled stand, I simulated a range of thinning densities. For example, stand 7 was simulation thinned to residual densities shown in table 1. The corresponding age 90 volumes also are shown. The residual density of 988 trees/ha (400 trees/acre) is the lowest density that comes closest to producing the nothin volume of 145 cubic meters/ha (2,081 cubic feet/ac). More than likely there is a closer answer, perhaps 1,139 trees/ha (460 trees/ac), but for the sake of this example, 1,139 trees/ha (400 trees/ac) is being used. One could conceptualize how the table could include intermediate cuts, if the minimum line was defined as that density that produced the most volume. The volume that I show in the table could include volume from intermediate cuts.

QUALIFICATIONS ON USE OF THE CURVES

In dealing with inventory samples, each sample responded differently in the PROGNOSIS model. It is apparent stands are stagnated that lie in the dashed portion of the maximum Stand Density Index line (fig. 8). The more manageable the stand, the lower the minimum line tends to be. I have illustrated the plot of a lodgepole plantation having thinning simulations starting at age 10. This leads me to conclude there isn't a specific minimum line, but rather a minimum band. Use of the PROGNOSIS allows the establishment of such a band. Stands advanced in age (in my example, say 50 years), and have been allowed to grow to a position near the maximum line, cannot be thinned to the residual density of a stand grown from sapling size under lower density. Tree vigor will not allow rapid reoccupation of the site, and as a result, merchantable fiber will be lost. Once a stand has been thinned to the minimum line, it will not track along the minimum line in the time remaining to rotation. The minimum line is the level thinned to and is not a growth line. Figure 8 shows how a stand thinned to the minimum level at age 30 tracks in terms of basal area from 30 to 90 years. Remember by my definition, volume at 90 years will be equal to that of the same stand not thinned at all.

The selected table value for each subsampled location was plotted on the stocking diagrams and a minimum line drawn through the plotted values. Figures 7 and 8 show the groups six minimum and maximum lines. Under a regime of frequent light thinnings, I might be able to produce more volume over the rotation.

CONCLUSIONS

PROGNOSIS can be used to derive a variety of stocking guides. The sample of stands simulated with PROGNOSIS must be carefully screened and categorized if the final tables are to reflect the even-aged forest. Simulation of true stagnated stands is to be avoided for the technique does not work well under such conditions. The choice of rotation age can and probably should include potential mountain pine beetle activity. The definition of management objectives must correspond with

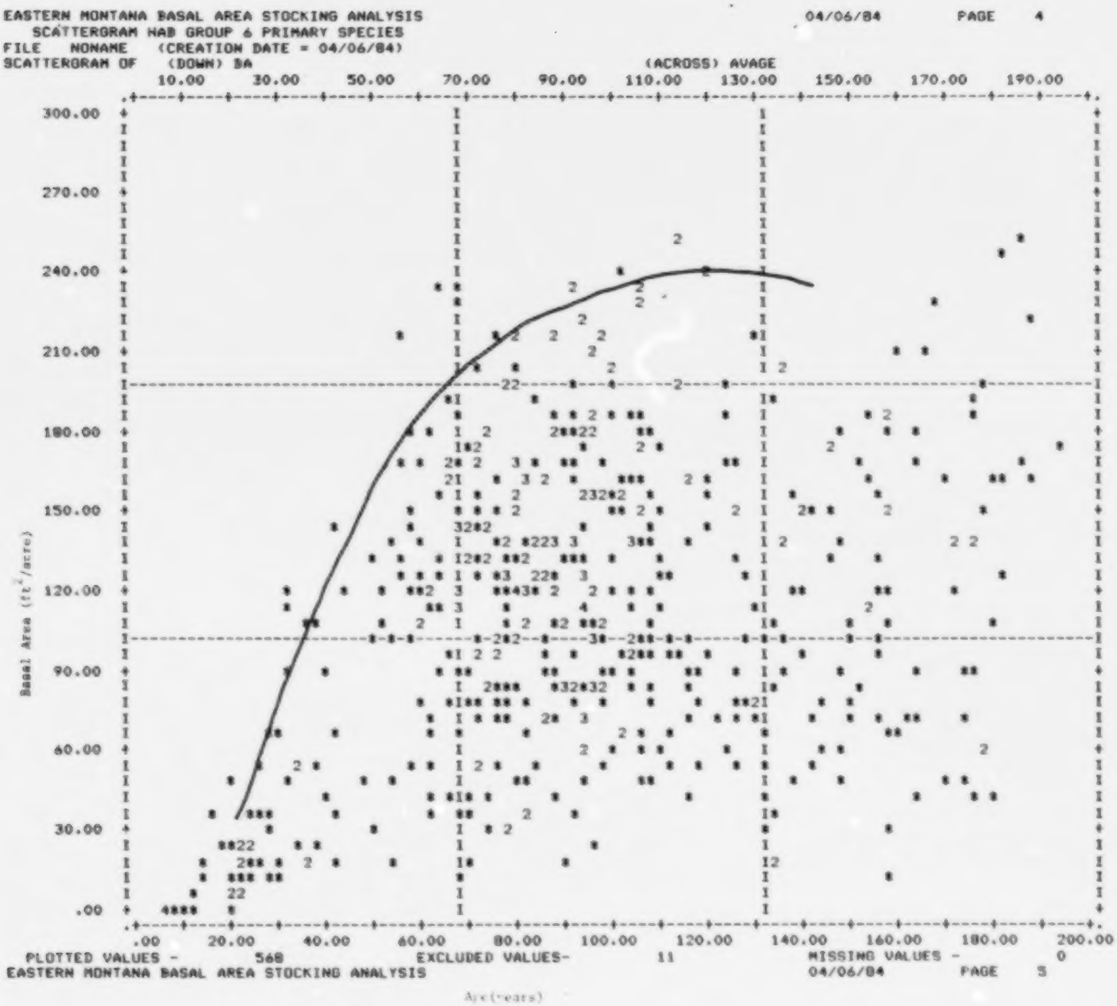

Figure 5.—Basal area/age scattergram. The basis for a maximum stand density level.

the rotation age selected. That is to say, to not derive management guides using commercial thinnings and specify rotations beyond the culmination of mean annual increment.

The use of simulation allows real field conditions to be included into selected stocking levels. Simulation also allows the comparison of a variety of management objectives in terms of stocking levels.

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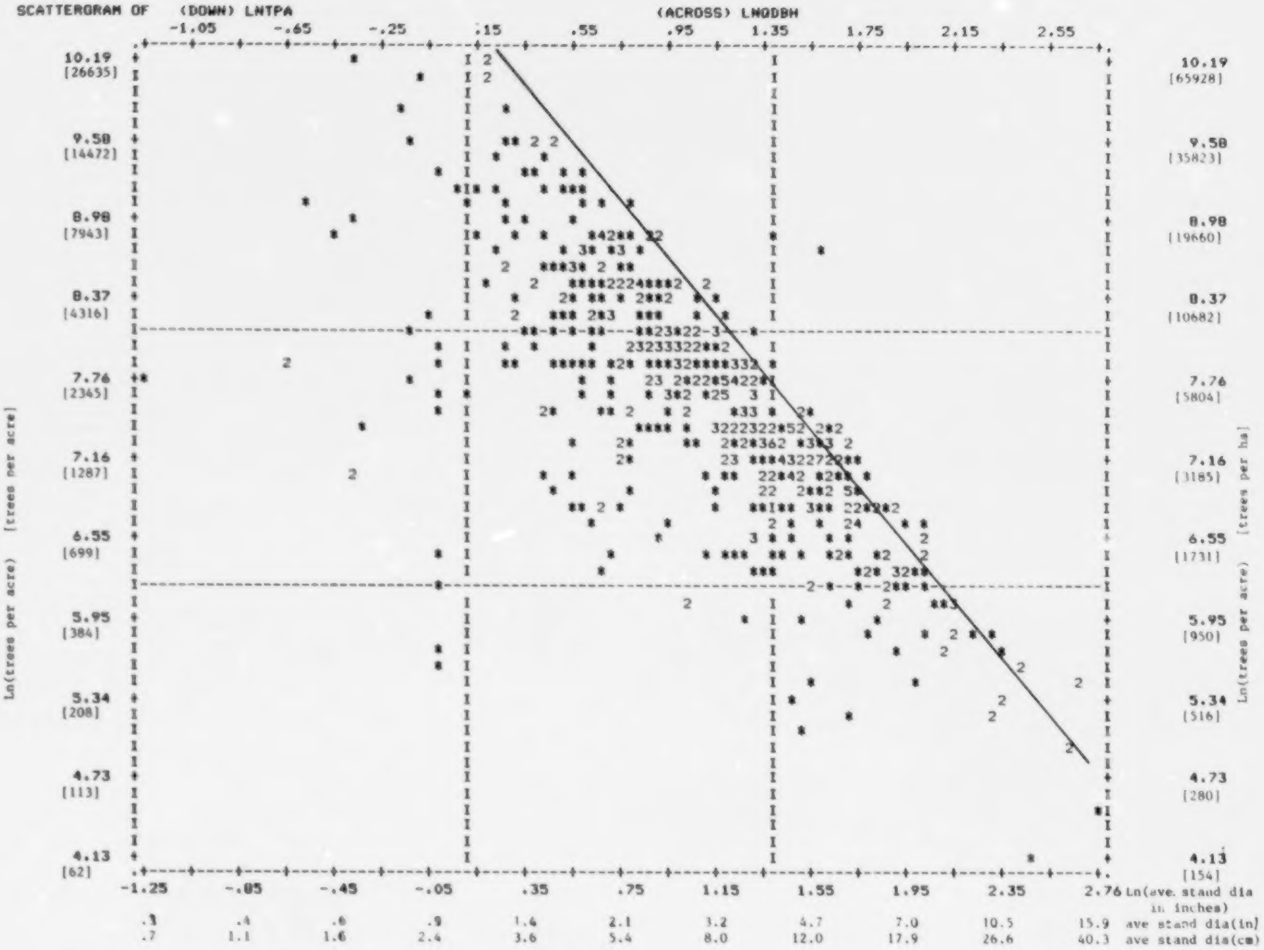

Figure 6. – Trees/ha (trees/ac) vs average stand diameter scattergram the basis for the maximum stand density index.

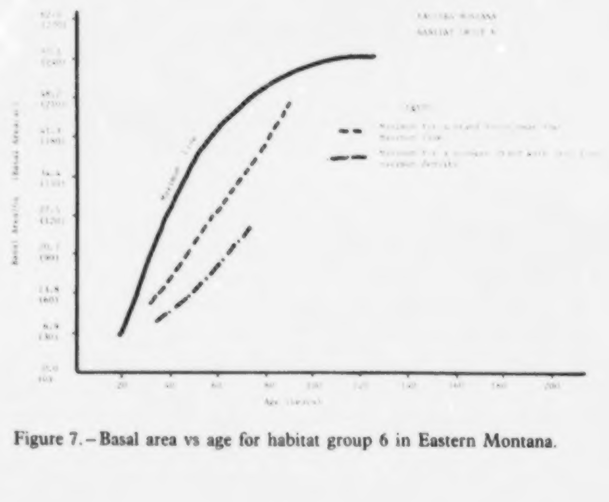

Figure 7. – Basal area vs age for habitat group 6 in Eastern Montana.

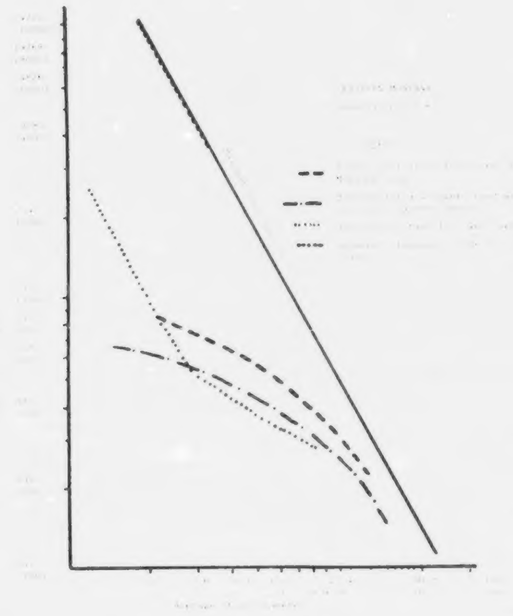

Figure 8.–Trees/ha (Trees/ac) vs average stand diameter for Eastern Montana habitat group 6.

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Table 1.–Cubic volumes diameter, basal area, and trees/unit area by residual density.

	Regime			
Attribute	No thin	thin to 1,235/ha 500/ac	thin to 988/ha 400/ac	thin to 741/ac 300/ac
Volume/ha (vol/ac) @ 90 years	145 (2,081)	136(1,946)	137 (1,159)	30 (1,859)
After thin B.A. cu m/ha (sq ft/ac)	5.7 (25)	5.0 (22)	4.8 (21)	4.8 (21)
B.A. at 90 years cu m/ha (sq ft/ac)	41.8 (182)	23.0 (100)	22.0 (96)	19.7 (86)
Avg. stand diameter after thinning cm (in.)	3.3 (1.3)	7.1 (2.8)	7.9 (3.1)	9.1 (3.6)
Avg. stand diameter @ 90 years cm (in.)	14.2 (5.6)	20.3 (8.)	22.1 (8.7)	23.9 (9.4)
Trees @ 90 years per ha (per acre)	2,663 (1,076)	708 (286)	577 (233)	441 (178)

A STAND DENSITY MANAGEMENT DIAGRAM FOR LODGEPOLE PINE

James W. Flewelling
and
T. John Drew

ABSTRACT

Stand density is the primary factor controlling growth and development of managed even-aged stands. A stand density management diagram is a graphical device which focuses attention on this relationship. Age and site are not emphasized.

Growth and mortality data from managed stands of *Pinus contorta* Dougl. in Oregon, British Columbia, Alberta, Finland, Sweden, United Kingdom and New Zealand was kindly provided by government agencies. This data was used in developing a common prediction equation for gross volume increment. This equation predicts that sixty percent of the maximum growth per unit area can be achieved at densities of about one-fourth the maximum. The same data was used to position mortality trend lines on the diagram.

INTRODUCTION

This presentation is mainly a summary of a research project by Weyerhaeuser Canada and the British Columbia Ministry of Forests.[1] The purpose of that research was to identify the size-density trade-offs inherent in the management of lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.). A second purpose was to estimate the growth rates which are likely to be obtained in the Interior of British Columbia.

Lodgepole pine is a candidate species for intensive management in the Interior of British Columbia. Because of its ecological adaptability, rapid early growth, relatively good regenerative ability, and excellent wood characteristics, lodgepole pine could assume a preeminent position in the Interior forest resource.

The management tools of immediate importance are regeneration strategies, and strategies for spacing and thinning. Regeneration is not addressed in this report. It is sufficient to note that regeneration, especially natural regeneration following wildfire or logging, is usually easy to attain. The usual problem is over-abundance of regeneration. This, together with lodgepole pine's apparent inability to thin itself, results in the dense stands of this species frequently seen in the Interior. In these dense stands, intraspecific competition is severe and individual tree growth and vigor is low. Indeed, it is quite unlikely that stands of more than 4,500 stems per hectare at 90 years of age will ever yield a merchantable volume (Smithers, 1961). Previous studies have demonstrated that lodgepole pine, particularly at young ages, responds well to thinning. Thus, spacing of these dense stands will be required if they are to be a part of the productive forest inventory. To space these stands will require an understanding of optimum management regimes and these are not yet developed.

The trade-off between stand density and tree size can be identified on a density management diagram. This is simply a graph of mean tree size over density on which certain trends and limits have been identified. Examples of density management diagrams are by Gingrich (1967), Aiba (1975), Lewis and others (1976) and Drew and Flewelling (1979). It is possible to construct such a diagram even though we may lack the data to construct a full growth and yield model.

Of interest in our study is the inland form of *Pinus contorta* (var. *latifolia*). This grows east of the coastal mountains, and occurs in all biogeoclimatic forest zones in the British Columbia interior (Krajina, 1969). The data limitation is that practically no managed stands exist in the interior of British Columbia. Further, the generally over-dense conditions in existing natural stands do not provide a good basis on which to estimate the potential of managed stands. Lodgepole pine is one of the few coniferous species where height growth is known to be greatly influenced by stand density. (Alexander and others, 1967).

The prospects for making good estimates of potential growth rates under management would be bleak if not for the extensive data from plantations around the world. Seed sources from this region have been used for extensive planting programs in Scandinavia, the United Kingdom and New Zealand. These plantations have been managed at a variety of densities, usually far below what are currently found to exist in natural stands. Growth data from these plantations can be used to quantify the size-density tradeoff inherent in the species.

MAXIMUM STOCKING RELATIONSHIP

The maximum stocking relationship plays the central role in our understanding of density effects.

Reineke (1933) observed that for a given species there is a limiting relationship between stand density and average tree size. On a log-log graph of trees per unit area over quadratic mean diameter, this relationship is a straight line. Furthermore, the slope of that line is about the same for most tree species. Reineke's maximum stocking relationship for lodgepole pine is:

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[1] Flewelling, J. W., W. D. Johnstone and T. J. Drew, 1984. Stand density management in lodgepole pine. A report to the Ministry of Forests. Weyerhaeuser Canada.

$$TPH_{max} = K_1 \ (DBH)^{-1.605} \quad (1)$$

where $K_1 = 1.50 \times 10^5$

DBH is quadradic mean diameter (cm)
TPH_{max} is trees per hectare

An analogous relationship between plant dry weight and density has been proposed and demonstrated by Yoda and others (1963). This − 3/2 power low is apparently applicable to a great number of plant species (White, 1975; Harper, 1977). A derivation of the relationship is reviewed by Drew and Flewelling (1977). In forestry, mean stem volume is often used rather than mean plant weight. This relationship, expressed in a form similar to that of Equation 1 is:

$$TPH_{max} = K_2 \ (\bar{v})^{-2/3} \quad (2)$$

where $\bar{v}$ = mean tree volume (m^3).

GROWTH AND YIELD DATA

Analyses were based solely on growth information from permanent plots. We are deeply indebted to the agencies and individuals who provided this data. The various data sets are now described.

Gregg Burn. – This study was installed by the Canadian Forestry Service near Hinton, Alberta (Canada) in the Upper Foothill Section of the Boreal Forest Region (Rowe, 1972). Three sites were selected within a naturally regenerated area. At each site, two blocks of five plots were established. Each plot was thinned to 494, 988, 1977, 3954 or 7907 trees per hectare at age seven. Measurements were made through age twenty-five. Results have been reported by Johnstone (1981a and 1983).

Mackay. – This study was also installed in a fire-origin stand by the Canadian Forestry Service in the Lower Foothill Section of the Boreal Forest Region (Rowe, 1972). At age twenty-two, four blocks were identified and a total of sixteen plots was installed. Treatments were assigned to each of thirteen plots. There were three unthinned control plots. The five treatments were square spacing at 1.5, 1.8, 2.4 and 3.7 m, and a square spacing at 1.8 m with a subsequent rethinning. Subsequent measurements were at ages twenty-eight, thirty-seven and forty-seven. Results are presented by Johnstone (1981b).

Tepee Pole. – This study was established in a twenty-five-year-old fire regenerated stand in the Upper Foothill Section of the Boreal Forest Region (Rowe, 1972). Study design was the same as at Gregg Burn. The stands had been extremely dense prior to the study installation (up to 250,000 stems per hectare). Subsequent measurements were at ages thirty and thirty-five. Results are presented by Johnstone (1982).

Nelson. – The EP385 spacing study was installed in a fifty-three-year-old fire-regenerated stand on a bench above the Kootenay River in southeastern British Columbia within the Columbia Forest Region (Rowe, 1972). The study consisted of a control plot and five spacings ranging from 2×2m to 5×5m. Subsequent measurements were at ages 59, 64, 69 and 74. Results are in an internal British Columbia Forest Service report.[1]

Finland. – Throughout Finland there are approximately 300 stands of lodgepole pine established before 1969. The Finnish Forest Resource Institute has maintained permanent sample plots. J. Nieminen of the Finnish Forest Research Institute made summaries of these plot data available to us. From these summaries, we selected eight plots with long-term growth information. These plots are located in six different stands. A second set of plot data was supplied by Mark Werren, also of the Finnish Forest Research Institute. These include plots in stands which were in two large block-type experiments.

Pringle Butte. – This spacing study was planted in 1967 by personnel of the U.S. Forest Service Silviculture Laboratory at Bend, Oregon. It is located in eastern Oregon near LaPine. Measurements used here were taken eleven and fifteen years after establishment. Data was provided by James Barrett. Five square spacings were used ranging from 1.8m to 5.5m.

Beatty Creek. – This is another eastern Oregon spacing study installed by the Silviculture Laboratory. Data were provided by Pat Cochran and Walt Dahms. The study design is the same as at Pringle Butte, but only lodgepole pine was used. The measurements used were at ages fourteen, sixteen, nineteen and twenty-two. Additional details and analysis are given by Dahms (1983).

Sweden. – The Institutet för Skogsförbättring has maintained permanent plots in a variety of lodgepole plantations. Most are in southern and central Sweden; provenances are of the latifolia variety, collected from latitudes above 50° north. Björn Hägglund provided us with data from a number of these plots. Used are data from the nine plots with the longest growth records.

New Zealand. – The Forest Research Institute maintains permanent plots throughout the national forests. John Tustin, Tricia Lönn and Judy Klitscher of the Production Forestry Division provided us with growth and yield summaries of plots in lodgepole pine plantations. We elected to use the data where the "yellow" (interior) variety had been planted. Most plots of these were from a Shuswap Lake (B.C.) source.

United Kingdom. – There were widespread plantings of inland varieties of lodgepole pine in Scotland, Wales and Northern England during the 1930's. J. M. Christie (U.K. Forestry Commission) provided growth summaries from plots within these plantations. There were thirty-seven plots at eight different locations.

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[1] Thompson, C. F. Thinning Experiment in Lodgepole Pine. Progress Report No. 3, EP384 and 385. B.C. Forest Service.

Fraser Lake Spacing Study. – This is the study EP671 of the British Columbia Ministry of Forests. The study is located within the Spruce Sub Zone of the Sub-boreal Spruce Zone[2]. Two provinces were planted in spring of 1968 at each of four spacings (1.8m × 1.8m to 3.7m × 3.7m). Measurements were made at five, ten and fifteen years after planting. An analysis at ten years after planting (Pollack, 1982)[3] demonstrated small but significant effects of spacing on tree growth rate. This data set was made available to us by J. Pollack.

MAXIMUM SIZE-DENSITY RELATIONSHIP

Trends of mean tree volume over trees per unit area were graphed on log-log scale for each data set. Graphs for several of the sets are presented as figures 1a through 1f. Families of straight lines with slope of − 1.5 were overlaid on the graphs. The lines were considered to be indexed by their intercepts on the graph. The lines within the range of the data were examined, and that line which was only exceeded by a few data points was taken to be the "maximum stocking line." This is sufficient to determine K_2 in Equation 2. We positioned the maximum stocking line by selecting K_2 in Equation 2. We positioned the maximum stocking line by selecting K_2 equal to 1016.

Relative density was then defined as:

$$P = TPH/TPH_{max} \tag{3}$$

where TPH_{max} is from Equation 2.

GROWTH AND MORTALITY MODELS

In modeling the effect of stand density on growth, we chose a model similar to that described by Möller (1954) for European beach (*Fagus sylvatica* L.). Gross periodic annual increment in volume (PAI) is proportional to a measure of density if density is very low. As density increases, the proportionality constant declines; at very high densities, growth rate is at a constant maximum value. An equation form which behaves this way was used by Flewelling (1981):

$$PAI = c_1(P)/(1 + (c_2)P) \tag{4}$$

where:

PAI = Gross periodic annual increments in volume

P = Relative density

c_1, c_2 = Constants, or functions of other stand parameters

The main growth model was:

$$\hat{PAI} = [B_L][P/(1 + C_1\ P)][H{**}C_2]{*}EXP(-C_3{*}H) \tag{5}$$

where $B_1....B_L$ are regression coefficients ("growth multipliers") used for locations 1....L respectively,

H is dominant height,

C_1, C_2, C_3 are regression coefficients common to all locations.

A weighted least squares regression produced the following results.

Coefficient	Estimate	Asymptotic Std. Error
C_1	4.2	.3
C_2	1.04	.1
C_3	.063	.01

Detailed results by data set are in the report to the Ministry. The location constants (B's) ranged from 9 to 14 for Alberta, 10 to 14 for British Columbia, 10 to 15 for Scandinavia, and 15 to 20+ for Oregon, the United Kingdom and New Zealand. These constants are directly proportional to productivity.

A mortality relationship was based on a regression fit to a subset of the data. That relationship is based on the trends of plots over time on graphs of mean tree volume versus TPH. An angle (M) was defined as the number of radians (1 radián = 57°) between a plot's trend line and a vertical line on that graph. The regression of M on relative density was fit as

$$M = b_1 + b_2\,(P)^{b_3} \tag{6}$$

$b_1 = .0466$ SE $(b_1) = .008$

$b_2 = 1.00$ SE $(b_2) = .14$

$b_3 = 3.51$ SE $(b_3) = .45$

Standard error of estimate = 0.09

This predicts that angle M increases with P. At the density where the tangent of M equals 2/3, P must be predicted to remain constant; hence, it is at this density that the predicted "mean maximum" density must occur. This can be solved for: P = 0.84. Hence, yield tables constructed with this relationship will have 0.84 as their highest predicted relative density.

One additional relationship was needed in order to produce the density management diagram. A dead-tree size relationship was used:

$$\bar{V}_{dead} = 0.45\ \bar{v}$$

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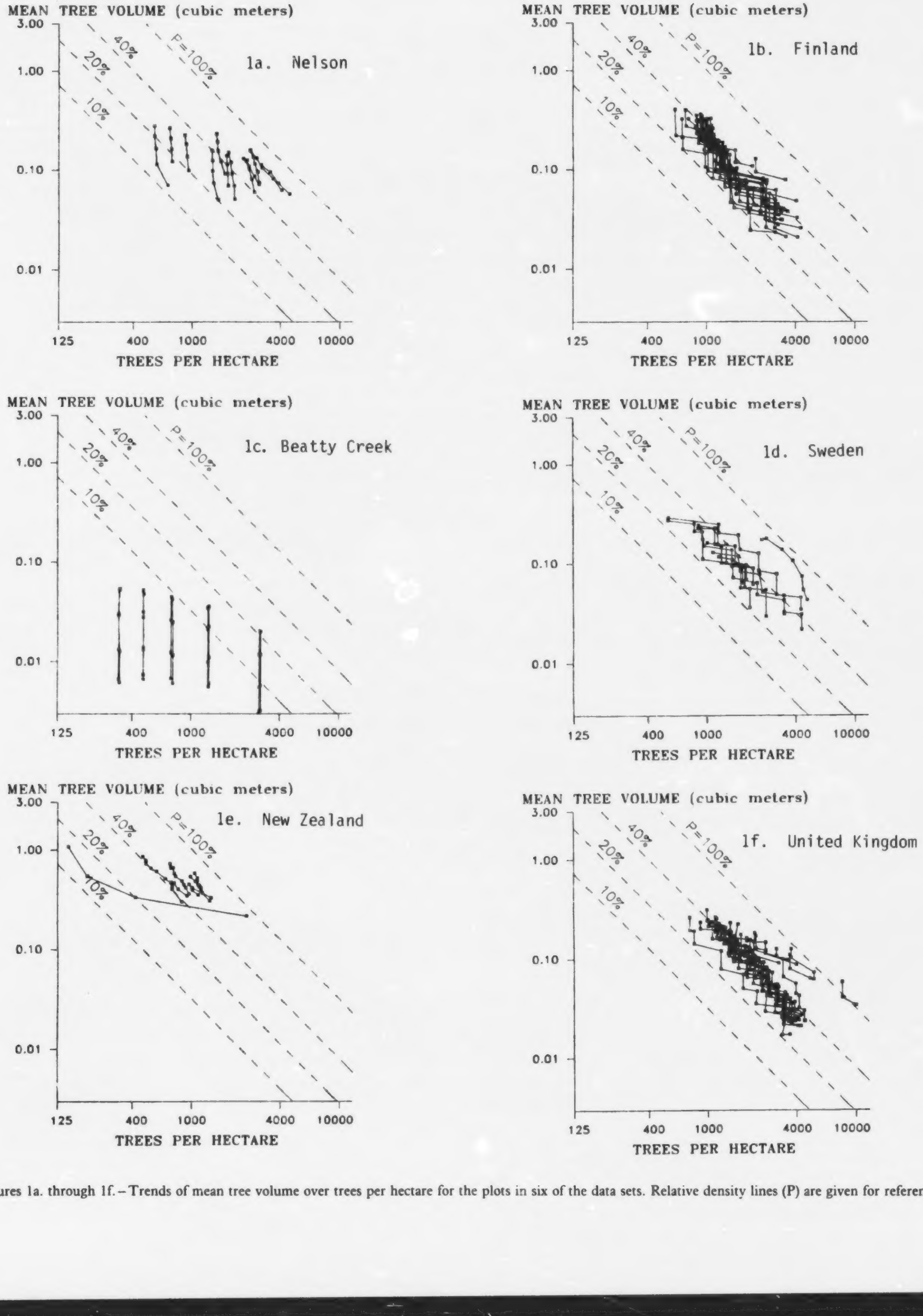
[2] McLeod, A., G. Hope and C. DeLong. Unpublished guide to the Sub-boreal Spruce Zone – Prince George. Prince George Forest Region. B.C. Ministry of Forests. Prince George, B.C.

[3] J. Pollack. 1982. The effects of initial escapement upon the growth and yield of lodgepole pine plantation – EP671. Five-and ten-year measurements. Internal report prepared at the B.C. Ministry of Forests – Prince Rupert Forest Region.



Figures 1a. through 1f.—Trends of mean tree volume over trees per hectare for the plots in six of the data sets. Relative density lines (P) are given for reference.

DISCUSSION

The foregoing relationships were used to produce a density management diagram. The metric version is figure 2 and the English version is figure 3. The diagram contains several relative density lines; these can be used to determine the correct relative density to use in the growth-density graph in the upper right-hand corner of the diagram. There are also several trend lines that can be used in predicting mortality as mean tree size increases. The discussion of the density management diagram for Douglas fir (Drew and Flewelling, 1979) should be helpful; even the diagram produced for that species should be approximately correct for lodgepole pine.

Growth projections were made for the spacing study at Fraser Lake. The location parameter (14.0) and the final measurements were used to start a series of fifty one-year growth estimates. The results are presented in Table 1. Comparable growth estimates using Swedish yield tables (Hägglund and others, 1979 and Hägglund, 1980) are much more conservative; beyond age forty, more mortality and less growth are forecast.

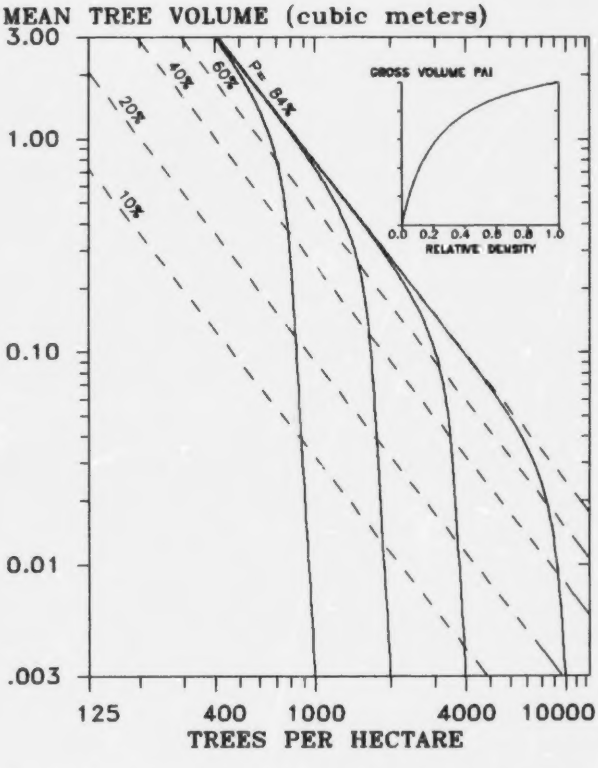


Figure 2. – Density management diagram (metric units) for interior lodgepole pine.

Table 1. – Comparison of Yield Predictions for 3.0m Spacing at Fraser Lake

Age (years)		Our Predictions		Swedish Yields	
Total	BH	TPH	Volume (m^3/ha)	TPH	Volume (m^3/ha)
18	12	978	15		
20	14	961	21	1000	30
30	24	898	83	987	103
40	34	858	184	921	186
50	44	824	310	826	264
60	54	784	445	720	334

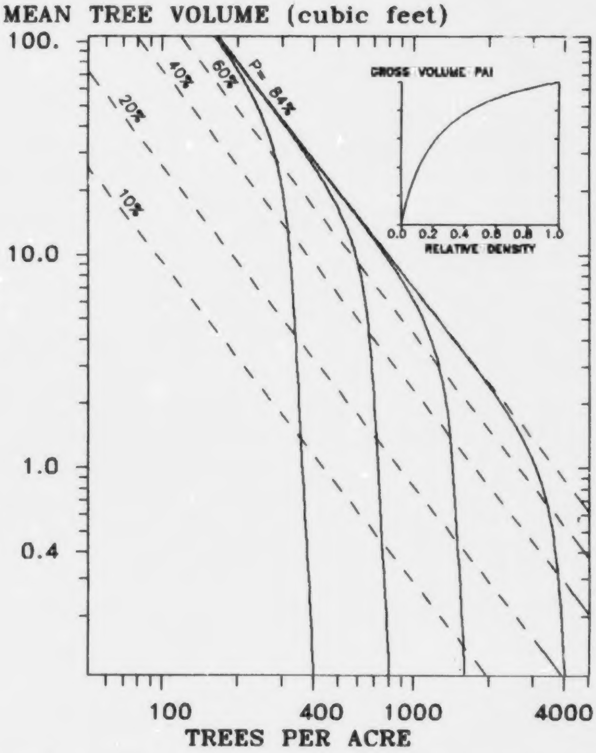


Figure 3. – Density management diagram (English units) for interior lodgepole pine.

The primary use of the density management diagram should be to plan management regimes. The mortality trends, together with the growth-density graph, should be the biological starting points for this process. However, productivity information (the B_i coefficients) will also be needed. This is not provided here; in the report to the Ministry, the location constants are available only for the sites that the growth data were obtained. An attempt to relate productivity to climate was for the most part unsuccessful. A highly variable relationship between productivity and temperature was graphed, but is not recommended for application to specific sites. Growth data from many more managed stands will be needed before good estimates of potential growth for the various geoclimatic zones can even be attempted.

For the few managed stands where some growth data is presently available, there are several ways to estimate future growth: 1) This model could be calibrated as was done for Fraser Lake and used for projections; 2) Site could be estimated and one of the managed stand yield tables entered (Hägglund and others, 1979 or Dahms, 1983); 3) A general purpose model such as PROGNOSIS could be used (Johnson, 1984). These methods will undoubtedly conflict with one another. All must be looked upon as very preliminary estimates of what might happen under management practices which have not yet been tested in the interior of the Pacific Northwest.

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STOCKABILITY AND MANAGEMENT OF LODGEPOLE PINE USING GROWTH BASAL AREA

Fred Hall

ABSTRACT

Stockability of pure, even-aged lodgepole pine is evaluated using growth basal area (GBA). GBA is the basal area at which dominant trees grow at the rate of 25 mm in diameter per decade. GBA is determined on site by relating current diameter growth rate to a curve for conversion to 25 mm diameter growth and applying a conversion factor to current basal area to obtain GBA. The USDA, Forest Service Ecology Program in Oregon and Washington has found more than one GBA for a lodgepole pine site index (SI) class (base age 50). SI 9 m can have GBA's of 11, 24, and 40 m^2 per hectare. SI 15 m can have GBA's of 22, 39, and 46 m^2 per hectare. GBA class 23 m^2 can occur in both SI 9 m and 15 m and GBA class 39 m^2 can also occur in SI 9 m and 15 m. SI is not a suitable index for estimating stockability.

The GBA concept is applied in this paper to prescribing number of residual trees per hectare following pre-commercial thinning for two management objectives: (1) Clearcut when trees reach 25 cm dbh and a diameter growth rate of 20 mm per decade and (2) commercially thin at 20 cm DBH and 30 mm diameter growth per decade. For example, residual trees per hectare for clearcutting and the corresponding crown competition factor (CCF) at harvest are: GBA 11 m^2 at 260 TPHa and CCF 87, GBA 23 m^2 at 505 TPHa and CCF 109, GBA 39 m^2 at 865 TPHa and CCF 150, and GBA 46 m^2 at 1015 TPHa and CCF 168. GBA, a function of diameter growth and basal area, is a useful tool for estimating stockability of a site.

INTRODUCTION

Lodgepole pine is widely distributed throughout the western United States and Canada. Plant communities in which it is an important component are being sampled and grouped into plant associations or habitat types through much of its range. In the USDA, Forest Service, Pacific Northwest Region ecology program, common tree species in each association are characterized for their productivity, regeneration, and successional status. Lodgepole pine can function as a climax dominant, an apparently stable or persistent species with questionable successional status, or is clearly seral to other tree species. Its successional status and classification are discussed by Dr. Volland in this symposium. The Appendix lists 39 plant associations with site index, growth basal area, total basal area, and number of plot samples per association for lodgepole pine.

Tree sampling used to characterize associations includes height, age, diameter growth, and diameter breast height (dbh) measurements of the five largest individuals of each tree species in a stand, and basal area (BA) is also calculated for each species. These largest trees correspond to dominants or the 125 largest trees per hectare.* Five to twenty-five stands are sampled for each association. From this information, average site index class (SI), growth basal area (GBA), and a productivity index by species are calculated for each association.

This paper deals with aspects of lodgepole pine stockability in Oregon and Washington because it is here where the growth basal area concept has been applied (Hall 1983). The need for stockability assessment of lodgepole pine is well recognized and has been extensively studied (Bella 1983, Dahms 1971, 1973a, 1973b, 1983, Duff 1964, Holmes and Tackle 1962, Johnstone 1983).

GROWTH BASAL AREA

Growth basal area (GBA) is the basal area at which dominant trees in pure, even-aged stands grow at the rate of 25 mm in diameter per decade (Hall 1983). Other trees in the stand will be growing at equal or slower rates. GBA is estimated according to tree growth performance on a site. Current rate of diameter growth per decade is measured (using the same dominant trees selected for site index class determination) and related to total stand basal area (BA).

Current rate of diameter growth is converted to a growth rate of 25 mm per decade using figure 1. This conversion factor is applied to stand BA adjusting it to that BA at which dominant trees would grow at 25 mm diameter per decade at age 100. For example, dominant trees might be growing at 20 mm per decade at 39 m^2/ha. The BA for 25 mm diameter growth must be lower than 39 m^2. Figure 1 shows this to be about 35 m^2/ha. Thus, GBA is a stockability index relating stand BA to 25 mm diameter growth of dominant trees based upon assessment of current stand performance.

Ecologists strive to sample variability in plant communities and thus the different kinds of sites in a geographical area. Poor sites, those stocked below what might be considered normal, as well as excellent sites, those stocked above normal, are sampled using natural, unlogged stands. The 39 plant associations (Appendix) in which lodgepole pine is an important species were sampled east of the Cascade Crest from the California to the Canadian border on National Forest System land.

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*English conversions: TPA = 0.405 (TPHa), ft = 3.28 (m), ft^2A = 4.36 (m^2/ha), ft^3/A = 14.29 (m^3/ha).

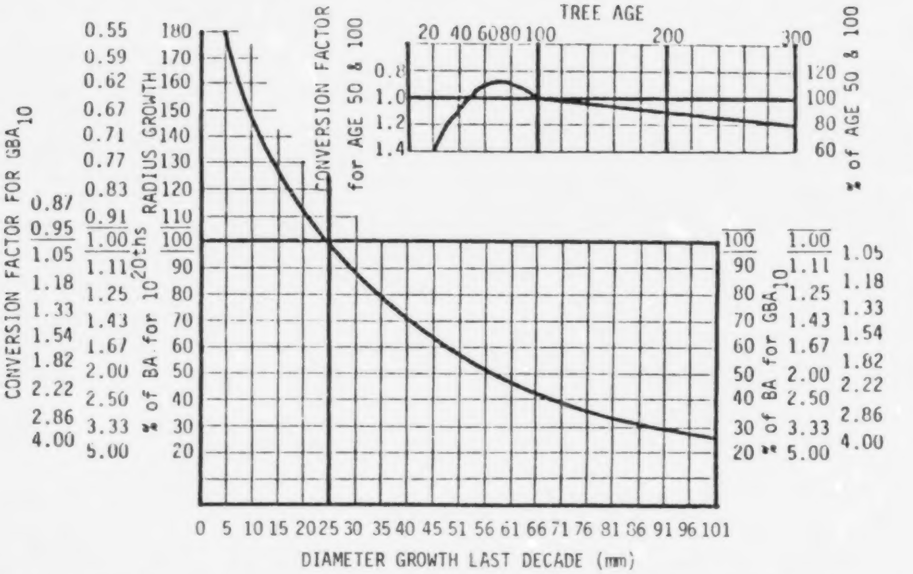

Figure 1.--Growth basal area (GBA) curve and age correction for estimating GBA for a stand. Procedure: determine age of dominant trees, total live basal area and current rate of diameter growth in the last decade; adjust current basal area to that for 25 mm diameter growth per decade. For example: current basal area 39 m^2/ha, age 100 (no correction needed), diameter growth 20 mm per decade; enter the graph at 20 mm, read up to the curve and left for 113 percent of GBA and a conversion factor of about 0.89; multiply times 39 m^2 for a GBA of 35 m^2/ha.

Stands were even-aged and range in age from 80 to 160 years. Average GBA for the associations varies from 9 to 46 m^2/ha. Average total basal area ranges from 14 to 53 m^2/ha. Total basal area may be used to compare these plant associations to other natural stands. In nearly all cases, diameter growth rate had slowed to less than 25 mm per decade.

GBA IN RELATION TO CCF

Crown competition factor (CCF) has been extensively used in lodgepole pine management. CCF is based upon stand diameter and basal area per unit area compared to open grown conditions (Alexander *et al.* 1967). There is no diameter growth function involved with CCF. For example, a stand with DBH = 10 cm and 37 m^2/ha has a CCF of 261. On a fair site, dominant trees in such a stand might be growing 20 mm in diameter per decade which would be a GBA of 33 m^2/ha. On a good site, dominants might be growing 30 mm in diameter per decade for a GBA 42 m^2/ha. Thus a single CCF can have more than one GBA because GBA is indexed to stand growth performance.

Dahms (1966) published two graphs which suggest closely related CCF's not only have different basal areas but also different productivities. Both stands were SI 15 m. At maximum cubic volume production, basal areas were 37 and 46 m^2/ha at CCF's of 265 and 298 respectively. Cubic volume productivities were 6 and 8 m^3/ha. Productivity was 134 percent and basal area 124 percent higher for the more productive site. This suggests diameter growth rate is somewhat greater at 46 m^2/ha, implying an even greater difference in GBA.

In addition, Dahms (1983) showed different productivities for CCF 150: 5, 7, and 8.5 m^3/ha/yr. The different productivities were partly a reflection of SI and partly a reflection of stand basal area. Apparently, a CCF class can have more than one productivity and GBA associated with it.

GBA IN RELATION TO SITE INDEX CLASS

Dahms (1966), clearly documented two cubic volume productivities for SI 15 m at very similar ages. Additionally, he found gross yield differences between Rocky Mountain and Pacific Northwest lodgepole pine stands for SI 24 m. The Rocky Mountain stands averaged 7.3 m^3 versus 4.5 m^3/ha/yr for the Pacific Northwest stands (Dahms 1973a). This illustrates that GBA must vary within a SI class. It suggests that GBA could be used to identify different productivities within a SI class.

GBA can be combined with SI to index stand productivity in the following manner: SI-GBA of 9-11 indicates SI 9 m and GBA 11 m^2/ha. SI indexes height growth, "G" of GBA indexes diameter growth, and "BA" indexes stockability.

Physiologically, it seems probable that different productivities can occur within a SI class because height growth tends to be a different physiological function from diameter growth (Kozlowski 1971). In general, height growth starts earlier in the season using stored food reserves, whereas diameter growth starts later, uses photosynthetically produced food, and tends to terminate under adverse growing conditions.

Correlation analysis of site features on SI and GBA support the concept that they tend to be separate growth functions influenced by different environmental factors. Hall (1971) regressed soil and topographic features on ponderosa pine SI and GBA for six plant associations. Of 21 features significantly correlated with SI or GBA, only four were associated with both SI and GBA. Analysis of the lodgepole pine/pinegrass-grouse huckleberry association of the Blue Mountains of Oregon yielded the following results for lodgepole pine SI and GBA:

(1) $\mathrm{SI} = 2.36(\text{A horizon pH}) + 1.88(\text{A horizon color}) - 12.7$

$\bar{x} = 12.2,\ \mathrm{SE} = 1.8,\ F = 15.1,\ R^2 = 0.81$

(2) $\mathrm{GBA} = 0.21(\%\ \text{slope}) - 0.08(\%\ \text{soil stone}) - 0.65(\text{B horizon texture}) + 39.9$

$\bar{x} = 27.1,\ \mathrm{SE} = 2.7,\ F = 14.5,\ R^2 = 0.88$

Elsewhere, site features have been significantly associated with lodgepole pine height growth or SI (Duffy 1964, Mogren and Dolph 1972, Smithers 1956). I assume that site features associated with GBA in these studies might be different from those associated with SI.

We have found more than one GBA per SI class for lodgepole pine in 39 associations in Oregon and Washington (Appendix). Figure 2 depicts SI and GBA relationships for these associations. Regression analysis suggests a very weak relationship between increasing SI and increasing GBA, significant at $P = 0.5$. The R^2 is only 0.16, suggesting that only 16 percent of the variability in growth basal area is accounted for by SI.

Six widely different associations are selected to illustrate variance of GBA with SI (table 1). SI's 9 m and 15 m each have three significantly different GBA's. GBA classes 23 and 39 m^2 occur in both SI classes 9 m and 15 m. This clearly suggests that an SI class may be misleading in estimating both stand productivity and stockability. It further demonstrates that a GBA class such as 23 m^2 which occurs in both SI 9 and 15 m, can have more than one productivity associated with it.

Figures 3, 4, and 5 depict the three associations in SI 9 m with GBA's of 11, 24, and 40 m^2/ha. The plant associations represent stands that grow at widely different locations on completely different soils in significantly different environments. These site factors apparently affect stockability more than site index.

USE OF GBA IN LODGEPOLE PINE MANAGEMENT

Table 2 reorganizes table 1 into four GBA classes of 11, 23, 39, and 46 m^2/ha. These GBA classes are used to illustrate residual tree stocking after precommercial thinning to meet first commercial harvest requirements. Early stocking level control in lodgepole pine has been clearly shown to be essential (Bella 1983, Dahms 1971, 1973a, 1973b, 1983, Duffy 1964, Holmes and Tackle 1962, Johnstone 1983). The purpose of pre-commercial thinning is to provide growing space for rapid initial diameter growth such as 100 mm per decade. As tree diameters and stand basal area increase, diameter growth rate will decrease to the point where commercial entry is desired.

Two kinds of commercial entries were selected: (1) clearcut and regenerate at 25 cm dbh and 20 mm diameter growth per decade, and commercially thin at 20 cm dbh and 30 mm diameter growth per decade taking 25 percent of the basal

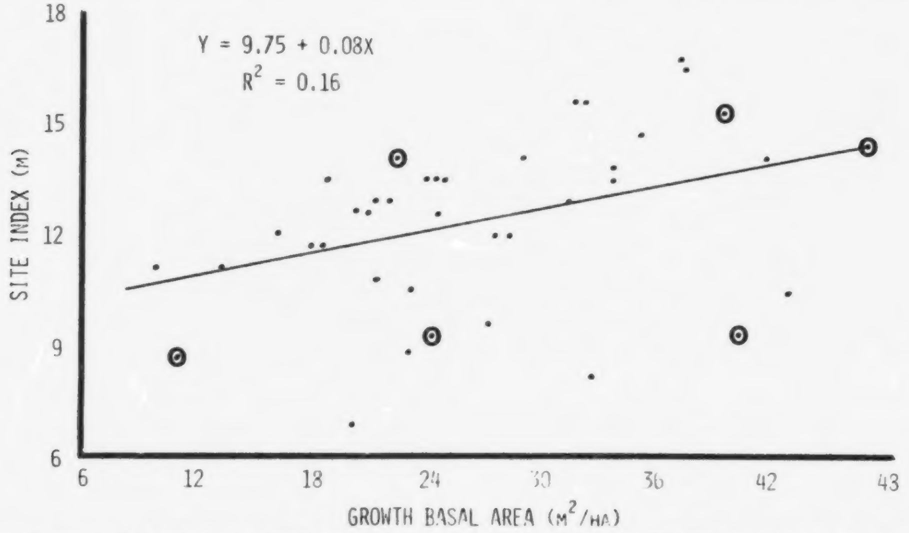

Figure 2.—Relationship of lodgepole pine site index to growth basal area for 39 plant associations in Oregon and Washington. Circled points are the six associations discussed in the text (Source: Appendix).

Table 1.–Differences in growth basal area (GBA) and stand basal area (BA) in two site index (SI) classes, base age 50, for six associations where lodgepole pine is either a climax dominant or a major seral species.

		SI Class 9 m	
GBA 10.6 m^2	BA 25.0 m^2	SI 8.8 m	Lodgepole/pinemat manzanita[1]
23.9 m^2	32.8 m^2	9.4 m	Lodgepole/big huckleberry[2]
39.7 m^2	48.0 m^2	9.4 m	Subalpine fir/grouse huckleberry[3]
		SI Class 15 m	
GBA 21.6 m^2	BA 27.6 m^2	SI 14.3 m	Lodgepole/bearberry[1]
39.0 m^2	48.9 m^2	15.5 m	Lodgepole/sedge-lupine-penstemon[1]
46.1 m^2	52.8 m^2	14.6 m	Subalpine fir/pinegrass[3]

1. Volland 1982 2. Hall 1973 3. Williams and Lillybridge 1983

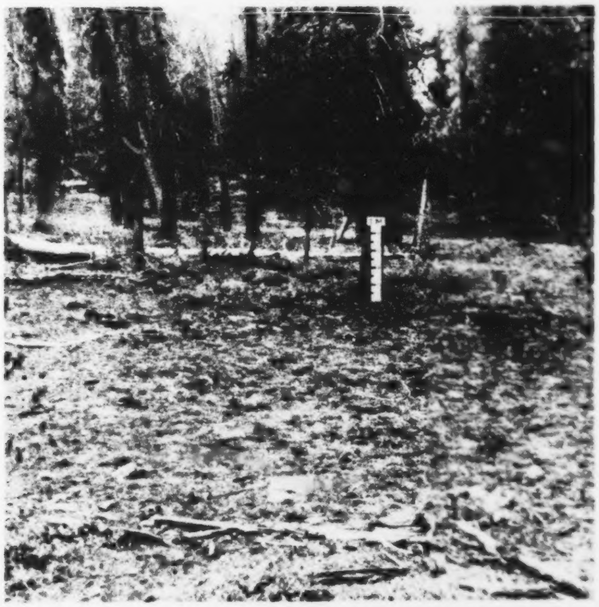

Figure 3.–Lodgepole pine/pinemat manzanita, characterized as SI-GBA of 9 m-11 m^2, is a high elevation, southern Cascade Range climax lodgepole pine association growing on Mount Mazama pumice with a majority of the soil particle sizes greater than 2 mm. The productivity index is only 1.0 m^3/ha/yr (Volland 1982). It is a typically poor lodgepole pine site with severe regeneration problems. Basal area of natural stands between ages 90 and 150 average 26 m^2/ha.

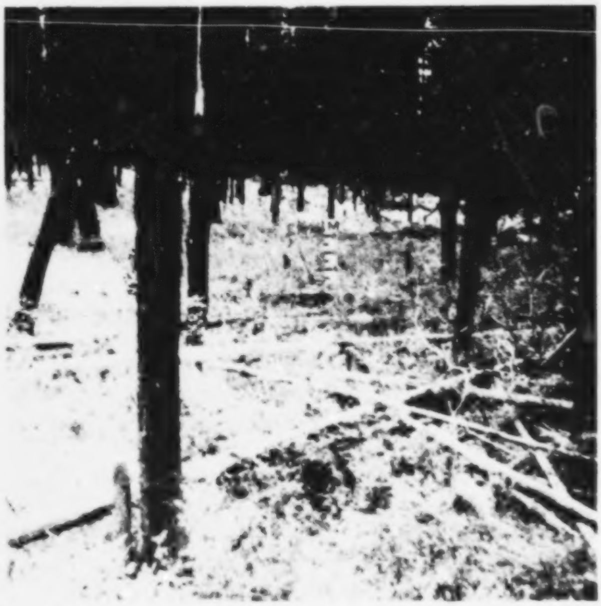

Figure 4.–Lodgepole pine/big huckleberry association, characterized as SI-GBA of 9 m - 24 m^2, which occurs in the Blue Mountains of eastern Oregon on a wind deposited ash soil of course silt particle size overlying buried soil. Lodgepole pine appears to be a persistent species because of insufficient grand fir regeneration and the very slow height growth of the few fir saplings which do occur. The productivity index is 2.3 m^3/ha/yr (Hall 1973). Brickel (1973) described a SI 9 m as growing 1.5 m^3/ha/yr based on 20 m^2/ha BA. Basal area of natural stands between ages 90 and 150 averages 33 m^2/ha.

Table 2.–Differences in site index (SI), base age 50, in four growth basal area (GBA) classes for six associations where lodgepole pine is either a climax dominant or a major seral species.

		GBA Class 11 m^2/ha	
SI 8.8	GBA 10.6	BA 25.0	Lodgepole/pinemat manzanita[1]
		GBA Class 23 m^2/ha	
SI 9.4	GBA 23.9	BA 32.8	Lodgepole/big huckleberry[2]
14.3	21.6	27.6	Lodgepole/bearberry[1]
		GBA Class 39 m^2/ha	
SI 9.4	GBA 39.7	BA 48.0	Subalpine fir/grouse huckleberry[3]
15.5	39.0	48.9	Lodgepole/sedge-lupine-penstemon[2]
		GBA Class 46 m^2/ha	
SI 14.6	GBA 46.1	BA 52.8	Subalpine fir/pinegrass[3]

1. Volland 1982
2. Hall 1973
3. Williams and Lillybridge 1983

Figure 5.–Lodgepole pine seems to be successional in the subalpine fir/grouse huckleberry association characterized by SI-GBA of 9 m - 40 m^2, in the Okanogan uplands of Washington growing on rather stony glacial till. The productivity index is 3.4 m^3/ha/yr (Williams and Lillybridge 1983). Basal area of natural stands between 90 and 150 years averages 48 m^2/ha.

area from below to increase diameter growth to 45 mm. The stand would be scheduled for clearcut regeneration at about 30 cm dbh and 20 mm diameter growth per decade.

Residual trees for these four GBA classes are shown in Table 3. For regeneration at 25 cm dbh, stocking ranges from 260 to 1015 trees per hectare (TPha) and CCF ranges from 87 to 168 at time of harvest. For commercial thinning at 20 cm dbh, stocking ranges from 310-1245 TPha and CCF ranges from 79 to 166 at time of thinning. Comparing Tables 2 and 3 suggests that SI 9 m can have 260, 505, and 865 TPha and SI 15 m can have 505, 865, and 1015 TPa for regeneration at 25 cm dbh.

SI alone lacks reliability for establishing stocking level guides for lodgepole pine. Even a CCF within an SI class poses problems because it does not identify a diameter growth–stand density relationship to establish a stockability index by which sites can be identified and characterized for management.

CONCLUSIONS

GBA is an index of stockability independent of site index class. It is determined in the field according to tree performance on the site. It is not a relative stockability index such as CCF, which can have a range of GBA's.

SI class is not a good indicator of stockability. A range of productivities may occur in a SI class which can be indexed by GBA. This suggests that a single maximum and minimum stocking for lodgepole pine may be misleading (Adams and Mogren 1974).

Table 3.—Lodgepole pine stocking after pre-commercial thinning for four growth basal area classes and two management systems with expected response.

		Growth Basal Area Classes m^2/ha			
		11	23	39	46
Regenerate at 25 cm dbh and 20 mm diameter growth per decade	Residual trees: (per ha)	260	505	865	1015
	BA when cut: (per ha)	13	26	44	51
	CCF[1] when cut	87	109	150	168
Commercial thin at 20 cm dbh and 30 mm diameter growth per decade taking 25% BA.	Residual trees: (per ha)	310	620	1060	1245
	BA when cut: (per ha)	10	20	26	40
	CCF[1] when cut	79	108	149	166
Residual BA for 45 mm diameter growth per decade	Residual BA: (per ha)	8	15	26	30
	Residual CCF[1]	70	89	116	128

1. CCF (Crown Competition Factor) estimated by: 50.58 + 5.25(BA/D) (Alexander *et al.* 1967).

GBA can be used to prescribe treatment for stands to meet desired diameter growth rates. It can be used for general planning by establishing GBA classes useful for computer simulation of stand growth or for mapping site potentials. It can be determined on-the-ground according to current stand performance as an aid in prescribing treatment tailored specifically to the site in question.

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APPENDIX

Plant associations in Oregon and Washington where lodgepole pine is either climax, persistent, or an important seral species. Associations where it is climax or persistent are named for lodgepole pine; where it is seral they are named for another tree species. Each association is characterized by site index at age 50, growth basal area, and total basal area of the sampled stands which were between 80 and 160 years old.

SI (m)	GBA (m^2/ha)	Total BA $(m)^2$/ha	Number Stands	Association Name	Auth.
7.0	19.3	35.6	10	Lodgepole-whitebark pine/sandwort	2
8.2	32.1	35.1	9	Douglas-fir/bearberry	4
*8.8	10.6	25.0	15	Lodgepole/pinemat manzanita	5
8.8	22.7	25.0	16	Lodgepole-whitebark pine/penstemon	2
*9.4	23.9	32.8	11	Lodgepole/big huckleberry	1
*9.4	39.7	48.0	27	Subalpine fir/grouse huckleberry	4
9.7	26.9	38.8	8	Subalpine fir/huckleberry/pinegrass	4
10.7	22.7	39.3	13	Lodgepole/grouse huckleberry	1
10.7	42.5	45.2	20	Subalpine fir/azalea	4
10.9	20.9	25.3	2	Lodgepole/bitterbrush-rhyolite	5
11.3	9.4	17.9	2	Lodgepole/sedge-needlegrass-basin	5
11.3	12.9	18.6	24	Lodgepole/needlegrass-basin	5
11.9	17.4	28.5	5	Lodgepole/ribes-bitterbrush/grass	5
11.9	18.1	30.1	21	Lodgepole/squirreltail-sedge	2
12.2	15.8	13.1	2	Lodgepole/sagebrush-rhyolite	5
12.2	27.1	27.8	9	Lodgepole/pinegrass-grouse huckleberry	1
12.2	27.8	38.6	24	White fir-lodgepole pine/sedge-needlegrass	2
12.8	19.7	25.7	13	Lodgepole/bitterbrush/forb	5
12.8	20.2	29.8	7	Lodgepole/needlegrass-lupine	5
12.8	24.1	34.4	12	Lodgepole/grouse huckleberry/sedge	3
13.1	20.7	30.5	10	Lodgepole/ceanothus-manzanita	5
13.1	21.6	26.2	4	Lodgepole/forb	3
13.1	31.0	34.2	8	Lodgepole/strawberry-Idaho fescue	2
13.7	18.4	25.7	30	Lodgepole/bitterbrush/needlegrass	5
13.7	23.9	36.5	7	Lodgepole/needlegrass-lupine linauth	5
13.7	23.9	37.0	5	Lodgepole/grouse huckleberry-pumice	5
13.7	24.1	26.4	19	Lodgepole/bitterbrush/Idaho fescue	5
13.7	33.3	34.9	14	Douglas-fir/vaccinium spp.	4
14.0	33.3	45.5	22	Subalpine fir/vaccinium spp.	4
*14.3	21.6	27.6	9	Lodgepole/bearberry	5
14.3	28.5	34.4	12	Lodgepole/vaccinium/forb	5
14.3	41.3	46.6	6	Lodgepole-aspen/strawberry	2
*14.6	46.1	52.8	8	Subalpine fir/pinegrass	4
14.9	34.7	45.0	8	Lodgepole/sedge-lupine	5
*15.5	39.0	48.9	6	Lodgepole/sedge-lupine-penstemon	5
15.8	31.2	33.5	5	Lodgepole/bitterbrush/sedge	5
15.8	31.7	32.8	5	Lodgepole/carex-needlegrass	5
16.8	37.0	44.3	5	Lodgepole/vaccinium/forb	3
17.0	36.7	41.3	3	Lodgepole/beargrass	5

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3. Hopkins 1979b
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THINNING LODGEPOLE PINE

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ABSTRACT

This review paper summarizes, from a growth and yield perspective, North American thinning research on lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.), discusses some of the risks associated with thinning lodgepole pine, and highlights some current Canadian thinning practices.

INTRODUCTION

The ability of lodgepole pine (*Pinus contorta* Doug. v *latifolia* Engelm.) to regenerate and survive in excessively dens stands following wildfire and logging is legendary. Stand densities exceeding 1,000,000 stems/ha have been observed in young stands (Smithers, 1957) and as many as 250,000 stems/ha have been reported in a 70-year-old stand (Mason, 1915). Seedling establishment is apparently unrelated to site quality (Horton, 1953) and, although heavy mortality may occur, dense stands tend to remain dense regardless of site quality (Smithers, 1961).

The degree to which stand density affects the growth and yield of lodgepole pine has been demonstrated (Alexander, 1974; Alexander *et al.*, 1967; Holmes and Tackle, 1962; Johnstone, 1976*b*; Smithers, 1956; Wikstrom and Wellner, 1961). Excessive stand density reduces average stand height, average stand diameter, and total and merchantable volume as shown in figures 1 to 3, respectively. Excessive stand density can effectively reduce the productivity of a high site to that of an average site, and so on (fig. 1-3). In addition, the rate and amount of mortality, the length of rotation, and the costs of harvesting are increased in high density stands. Fortunately, thinning can mitigate these adverse effects. By increasing the available growing space per tree, thinning reduces crowding and concentrates stand growth on potential crop trees with the ultimate objective of increasing the future yield and value of usable materials from the stand. Thus thinning allows the forest manager to control future tree size and quality, stand yield, and rotation length.

The objectives of this review paper are: (a) to summarize and discuss North American growth and yield research results relevant to the thinning of lodgepole pine, (b) to discuss some of the risks associated with thinning lodgepole pine, and (c) to highlight some of the thinning practices currently applied in Canada.

A REVIEW OF THINNING RESEARCH

Thinning can be characterized by a number of elements including type, weight, cycle, level of growing stock, and intensity. Few existing lodgepole pine thinning studies have held the remaining elements constant while testing the effect of one element. Indeed, in many of the existing studies the thinning treatments have been subjectively and qualitatively defined. Cole (1975) outlines some additional difficulties of summarizing the results of thinning research conducted to date.

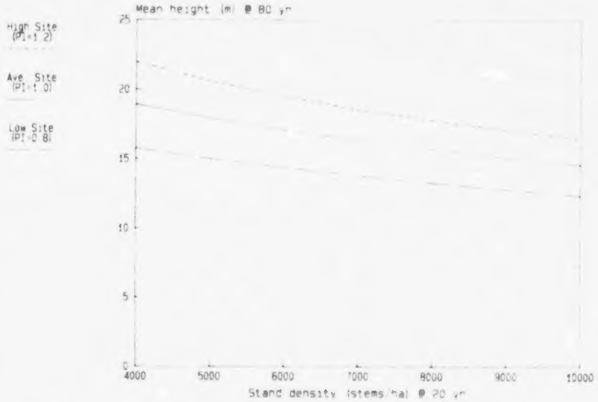

Figure 1.–The effect of stand density at age 20 yr on the mean height, at age 80 yr, of trees ≥ 1.5 cm dbhob in natural, unmanaged stands of lodgepole pine (Johnstone, 1976*b*)

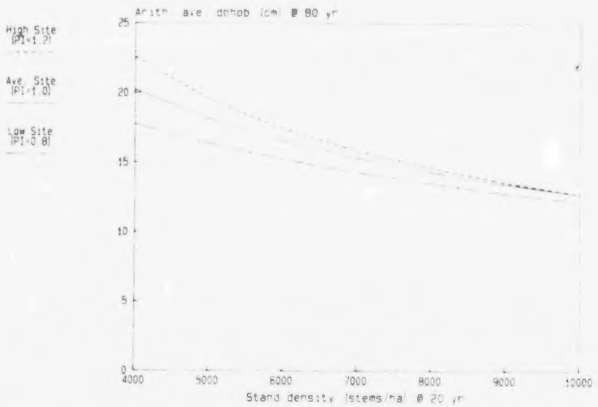

Figure 2.–The effect of stand density at age 20 yr on the average diameter, at age 80 yr, of trees ≥ 1.5 cm dbhob in natural unmanaged stands of lodgepole pine (Johnstone, 1976*b*)

Diameter Response

Virtually all investigations have shown that the effect of thinning on diameter development is dramatic and direct. Except in partially cut mature stands (Blyth, 1957), diameter growth is significantly increased in response to thinning (Alexander, 1956, 1960, 1965; Barrett, 1961; Cole, 1975; Dahms, 1967, 1971*a*, *b*, *c*, 1973; Daniel and Barnes, 1959; Johnstone, 1981 *a*, *b*, 1982 *a*, *b*, 1983; Smithers, 1957, 1961). For example, eighteen years after spacing a 7-year-old stand, Johnstone (1983)

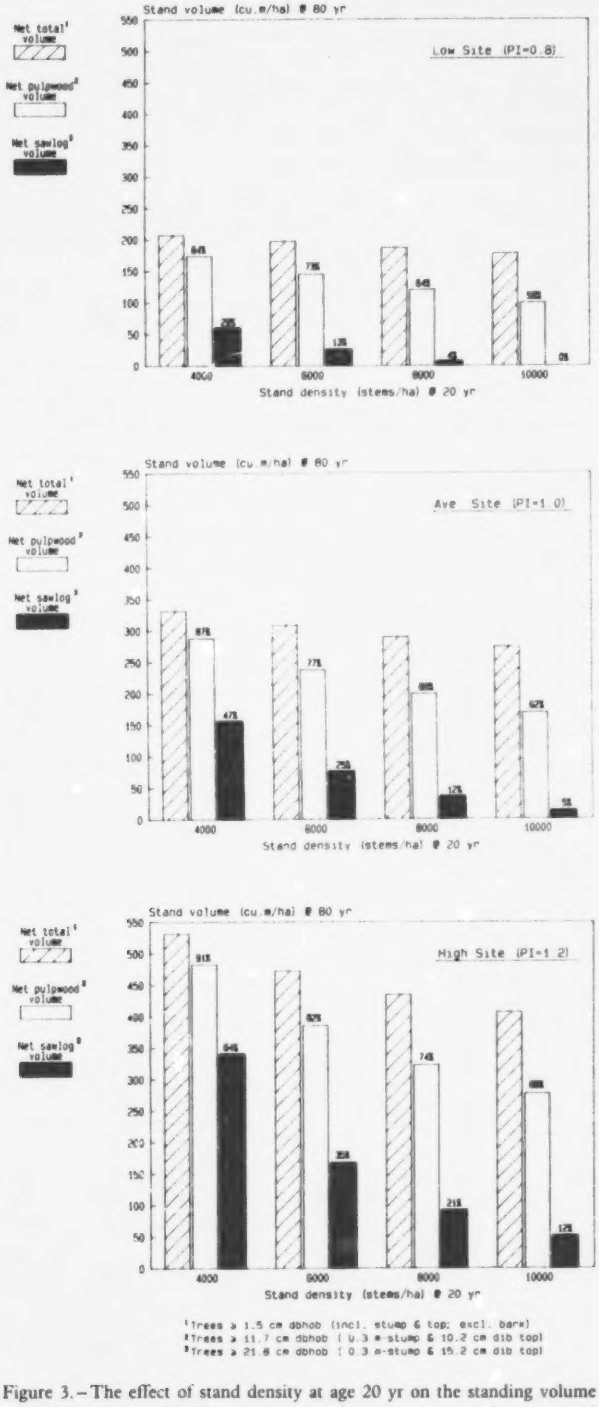

Figure 3. – The effect of stand density at age 20 yr on the standing volume and distribution (% of total volume) at age 80 yr in natural, unmanaged stands of lodgepole pine (Johnstone, 1976*b*)

reported an 89% larger mean diameter and a 131% larger 5-year periodic diameter increment (from ages 20 to 25 years) at a density of 494 stems/ha compared to a density of 7907 stems/ha. had resulted in a substantial alteration of the diameter distribution 25 years after thinning a 22-year-old stand. In this latter study, the shift to larger diameter classes increased with spacing and resulted in 81.7% of the growing stock in the 3.7 x 3.7 m spacing attained small roundwood sizes (≥ 12.4 cm dbhob), compared to only 2.4% in the unthinned stand (10 679 stems/ha at age 22 years). Although Dahms (1971*b*, *c*) found little relationship between initial diameter and subsequent diameter response, this study (Johnstone, 1981*b*) confirmed Smithers' (1957) results which found diameter growth response to increase with initial tree size.

Based upon the available literature, the following general conclusions can be drawn regarding the relation between thinning and diameter growth response:

1. Response to thinning is directly related to the weight of the thinning; therefore, thin heavily for greater response.
2. Absolute growth response appears to be greatest on high sites, but the greatest relative response appears on low sites; therefore, thin more heavily on low sites.
3. Response to thinning is inversely related to age; therefore, increase the weight of the thinning as age increases.
4. Growth response appears to increase with initial tree size; therefore, thin from below favoring healthy and vigorous dominant and co-dominant crop trees.

Height Response

By its very nature, thinning from below automatically increases the mean height of the thinned stand. However, unlike diameter response, the reported responses to thinning in terms of height growth are less dramatic and less conclusive. The lack of consistent height growth response is paradoxical because, as shown previously, the adverse effect of excessive stand density on the height development of lodgepole pine can be clearly demonstrated. The variability of reported research results probably reflects the important influences of both age and site quality on height growth response to thinning. For example, Smithers (1957) reported a definite height growth stimulation following the thinning of a 5-year-old stand but no response to the thinning of 40- to 70-year-old stands. Johnstone (1981*a*, 1983) reported significantly larger height increment at wider spacings in young stands on poor and intermediate productivity sites, but not on good sites, and speculated that this might reflect more intense competition for nutrients and moisture on the lower sites. In fact, wide spacing may even reduce height growth, particularly on high sites, because here tree crowns expand so rapidly that diameter increment accelerates at the expense of height growth (Johnstone, 1983). A comparison 18 years after spacing a 7-year-old stand indicated that, for a given diameter, trees grown at wide spacings were significantly shorter than trees grown at close spacings. Variable, but often modest, positive height growth responses have also been reported for thinning in comparatively older stands (Barrett, 1961; Dahms, 1967, 1971*c*; Gary 1978; Johnstone, 1981*b*, 1982*b*). On the other hand, Alexander (1960, 1965) found no consistent relationship between height growth and age or stand density in studies conducted in Colorado and Wyoming. There is some indication that a limited degree of crowding is required to maximize the height growth of lodgepole pine (Alexander, 1960; Dahms, 1973; Johnstone, 1981*b*, 1982*a*, 1983).

Basal Area Response

According to Smithers (1957, 1961), the basal area of fully stocked lodgepole pine rises rapidly in young stands and culminates at 40 to 50 years. At about 60 years, although gross basal area continues to increase, these stands reach a maximum net basal area level, consistent with site quality, which remains fairly stable thereafter until the stands begin to break up because of over-maturity. Most studies suggest that basal area increment increases with increasing residual stand density after thinning (Alexander, 1960, 1965; Barrett, 1961; Dahms, 1971*b*, *c;* Daniel and Barnes, 1959). Spacing studies of young stands (Johnstone, 1981*a*, 1983) show that net stand basal area increases with post-spacing density, but that there is a fairly wide range of density over which net basal area increment is essentially the same. Other studies (Johnstone, 1981*b*, 1982*b*) have shown that although gross basal area increment was reduced in thinned stands, their net basal area increment exceeded that of the unthinned stands. In general, the rate of basal area increment increases with increasing site productivity and declines with increasing stand age.

It is evident that, to optimize net basal area production, thinning prescriptions must:

1. be developed on a site-specific basis;
2. maintain an adequate level of growing stock to capture the productivity of the site, and
3. provide sufficient time, in advance of harvest, to allow for the accumulation of increment.

As a general recommendation, Smithers (1957) suggested a "well-distributed" thinning of up to 50 percent of the basal area for middle-aged stands with pre-harvest recovery period of at least 25 years.

Volume Response

Conventional growth and yield theory suggests that, at a given age, the total cubic volume production of fully stocked stands, on a given site, will remain constant over a wide range of stand density. Furthermore, conventional yield theory suggests that thinning can reduce, but not increase, this constant level of production. The range of stand density encompassed by this theory includes full site occupancy at the one extreme, and the point at which height growth is suppressed at the other extreme. In the case of lodgepole pine, the range of density required to optimize total productivity may be very narrow indeed. There is no doubt that the thinning of excessively dense, young lodgepole pine stands, in advance of suppression, will increase the total volume of these stands as they approach maturity. In older stands, if the improvement in stand height resulting from thinning from below can be maintained until harvest, and if, given sufficient time, the basal area of a thinned stand can increase to the level of the unthinned stand, then thinning may in fact increase total stand productivity.

Despite significantly larger and faster-growing trees at wider spacings, lower total volume and total volume growth per hectare at wide spacings are generally observed because of the disproportionately higher number of stems at closer spacings. Dahms (1967) observed an increase in total cubic volume increment with increasing stand density. Alexander (1965) and Dahms (1971*b*) reported comparable total volume increments in thinned and unthinned stands, after an initial reduction in increment following thinning. Twenty-five years after thinning, Johnstone (1982*b*) reported significantly lower total standing volumes, but significantly higher net total volume increments in thinned than in unthinned stands. This apparent contradiction of results may reflect not only the diversity of thinning regimes tested, but also differences in stand age at the time of thinning and the relatively short time over which most studies have been observed.

From a forest manager's viewpoint, the degree to which thinning affects the usable volume and value production of the stand is more important than whether or not thinning affects total cubic volume production. All studies conducted to date confirm that judicious thinning can increase the merchantable yield of lodgepole pine stands. Thinning can either prevent the loss of merchantable volume caused by growth suppression or recover merchantable volume from mortality in older stands. Wide spacing ensures the early attainment of merchantable trees in young stands (Johnstone, 1983). By stimulating the growth of the residual trees, thinning concentrates the growth potential of the site on fewer, larger and more valuable trees (Alexander, 1965; Dahms, 1967, 1971*c*, 1973; Johnstone, 1981*b*). The degree to which thinning can impact the economic yield of a stand can be understood with an examination first of price/size gradients, which clearly show the premium applied to greater tree dimensions and the products cut from large trees; and second of the lower harvesting (Schweitzer, 1975) and milling costs (Dobie and McBride, 1964), per unit volume, associated with larger trees.

In addition to growing larger trees at a given age, heavy thinning can grow trees of a given size sooner (Johnstone, 1981*b*). Furthermore, although the growth stimulation is small, thinning may marginally improve the merchantable yield of older stands, particularly when most of the stems are just below the threshold of merchantability (Johnstone, 1982*b*). Both practices may be of interest for relieving impending timber supply problems. However, it should be recognized that, because thinning generally increases the age at which mean annual increment culminates, the harvesting of stands that achieve a target diameter in advance of this culmination age will reduce the long-run sustainable yield (physical rotation annual allowable cut) of those stands over several rotations.

Risks Associated With Thinning

Having summarized the potential physical responses of lodgepole pine to thinning, it is also important to consider some of the circumstances that may enhance or jeopardize these responses and our investments in thinning. Stage (1975) identified an increasingly important need to accurately assess the interactions of pests and the growth of lodgepole pine. Although some research has been initiated (Ives, 1983), there is still an urgent need for a comprehensive evaluation and study of risks and uncertainties associated with the management of lodgepole pine.

Foresters have traditionally relied on intuition and experience to guide their regulation of long-established forests. Unfortunately, the problems associated with managed stands cannot always be easily related to experience formed under old-growth conditions. Because thinning improves individual tree vigor and reduces the environmental stress associated with excessive stand density, crop trees have an improved capability for resisting and recovering from attacks by most forest pests. On the other hand, in intensively managed forests, each crop tree assumes a greater importance from a yield point-of-view because a vigorous neighbor is not available to replace a tree that dies.

Thinning shows considerable promise as a means of reducing the risk of attack from lodgepole pine's most serious enemy, mountain pine beetle (*Dendroctonus ponderosae* Hopk.). Mountain pine beetle attacks are virtually unknown in stands less than 60 years of age, and are rare in stands 60 to 80 years old. Because high tree vigor reduces susceptibility to attack (Mitchell *et al.*, 1983; Safranyik *et al.*, 1974), thinning appears to be a valuable tool for managing this insect. Conversely, thinning may increase the risk of losses in crop-tree growth and quality, or mortality caused by other insect pests. For example, excessively dense stands generally provide poor habitats for Warren's collar weevil (*Hylobius warreni* Wood). If weevils are present in a stand, thinning may increase the rate of weevil development and maturity by increasing the temperature of the litter layer of the forest floor. Because collar weevils normally initially attack dominant and co-dominant trees (Cerezke, 1974) and because they can continue their development in stumps up to two years after cutting (Cerezke, 1973), the potential for collar weevil population build-up in spaced stands is increased. Similarly, the lodgepole terminal weevil (*Pissodes terminalis* Hopping), which is widely distributed throughout the range of lodgepole pine, may also require special consideration in the development of thinning guidelines. Trees attacked by the terminal weevil commonly exhibit severe stem deformities and substantially reduced height growth. The terminal weevil, which preferentially attacks the larger terminal shoots of dominant and codominant trees, can complete its development in the leaders of cut trees and, like the collar weevil, prefers the environment of low density stands (Maher, 1982). Consequently, thinning may also contribute to the increase of terminal weevil populations.

The probability of damage or mortality caused by various pathogens must also be considered before thinning is undertaken. For example, shoe-string rot infections(*Armillaria mellea* (Vahl, ex Fr.) Krummer), which spread from central foci with time, can create large, unproductive openings within stands and substantially reduce future yields (Johnstone, 1981*a*). Although lodgepole pine is considered to be only moderately susceptible to this root disease, spacing is not recommended in areas with ten or more disease centers per hectare (Morrison, 1981). In areas with fewer, scattered disease centers, normal spacing can be carried out except around the centers, where no trees should be removed. Dwarf mistletoe (*Arceuthobium americanum* Nutt. ex Engelm.) is a widely spread parasite which can seriously reduce the growth and quality – or kill – lodgepole pine trees. Although research in managed stands is limited, there are indications that thinning may create ideal light conditions for mistletoe seed production, and that light thinnings may enhance seed dispersal. However, Van Sickle and Wegwitz (1978) reported reduced mistletoe infection rates in selectively thinned stands and Hawksworth (1978) reported substantially improved yields in response to sanitation thinnings in lightly infected stands growing on high quality sites. Because spores are transported by wind, the areal rate-of-spread of rusts may also be affected by wide spacing. Of particular concern in thinning lodgepole pine is western gall rust (*Endocronartium harknessii* (J.P. Moore) Y. Hiratsuka) which, if it infects the bole, can reduce growth, quality, and increase wind-break susceptibility (Johnstone, 1981*a*). Avoidance of heavily infected stands and selective thinning in lightly infected stands may lessen the risk of losses to gall rust.

Of growing concern in Alberta and the interior of British Columbia is the interaction between thinning and small mammals. Daniel and Barnes (1959) demonstrated the degree to which porcupine (*Erethizon oxpixanthum* Brandt) damage can impact yield response to thinning. Recent studies by Sullivan and Sullivan (1982*a, b*) in British Columbia, and by Johnstone (1981*a*) and Powell (1982) in Alberta, report extensive barking injuries to lodgepole pine by snowshoe hares (*Lepus americanus* Erxleben) and red squirrels (*Tamiasciurus hudsonicus* Erxleben). These injuries result in either lost growth or mortality of crop trees. According to Sullivan and Sullivan (1982*a, b*), snowshoe hares apparently prefer to attack the small diameter trees of dense stands, but the amount of bark and vascular tissue removed per attack was nearly double in spaced, compared to unspaced, stands. The timing of precommercial thinning operation, to coincide with declines in the hares' population cycle, appears to be a critical factor in minimizing the risk associated with damaged caused by this animal. By comparison, red squirrels prefer to feed on larger diameter trees and the level of damage was significantly higher in spaced than unspaced stands. Unlike the hare, a well defined population cycle has yet to be identified for red squirrels, and the merits of the treatment timing strategy are presently unknown for this animal.

Summary Comments

To some extent, the deficiencies of the individual thinning studies can be overcome by the collective consideration of the large number of studies, thus leading to the following general conclusions:

1. Thinning can significantly enhance the merchantable yield and value of excessively dense stands.
2. The larger absolute response to thinning will occur on higher productivity sites and the greater relative response will occur on lower productivity sites.
3. A larger thinning response will occur in younger rather than older trees.
4. The largest growth response will occur in the larger dominant and co-dominant trees.
5. Individual tree response generally increases with increased thinning weight.
6. Thinning may increase some risks and reduce others associated with managing lodgepole pine.

However, these generalities are of little direct value to the forest manager faced with setting priorities for a broad array of silviculture alternatives. For example, what are the optimum thinning regimes and their predicted responses for a variety of age, site and stand density conditions? Should a greater-than-optimum density be retained following thinning, in anticipation of mortality losses? Fortunately, computer simulation and mathematical programming techniques are available or are being developed to assist the forest manager in examining these and other management alternatives.

Several simulation models have been specifically developed for lodgepole pine (Dahms, 1983; Lee, 1967; Myers 1967) and other models, STEMS and TASS, are presently being adapted for use with lodgepole pine (Canadian Forestry Service, 1982; Goudie and Mitchell, 1982). Models may be used to examine various thinning regimes (Cole, 1975), to predict mortality (Hamilton and Edwards, 1976), or to determine the interaction between thinning and pests (Hawksworth, 1978). Stage's stand Prognosis model (Wykoff *et al.*, 1982), which evaluates the most extensive range of stand management alternatives including stocking control, regeneration methods, site preparation and pest management, is currently used in the Inland Empire, although more calibration is needed for Canadian conditions. Mitchell's TASS model (Mitchell, 1969) is currently undergoing extensive calibration in Canada (Goudie and Mitchell, 1982) with a view to developing managed-stand yield tables for British Columbia and Alberta.

Although this review has been limited to North American experience with lodgepole pine, a brief comment on European experience with this species is warranted. Interior provenances of lodgepole pine were first introduced into Great Britain in the mid-1850s, into Sweden around 1910, and into Finland during the 1920s. Since this introduction, considerable knowledge has been gained concerning the yield implications of various silvicultural practices including thinning. Of particular interest are the managed-stand yield estimates developed in Britain (Hamilton and Christie, 1971) and in Sweden and Finland (Hagglund *et al.*, 1979), which incorporate various plantation espacements and subsequent thinning regimes. Although not directly transferable to North America, these European estimates may help compensate for our own limited experience in intensive stand management, and should provide some guidance and a useful comparison for our own managed-stand estimates as they develop.

AN OVERVIEW OF CANADIAN THINNING PRACTICE

The precommercial thinning of lodgepole pine has had a varied history in Canada. In Alberta, approximately 11,000 ha of fire-origin and second-growth stands have been thinned by the Alberta Forest Service and industry during the last 20 years.[1] A large portion of this area was thinned mechanically during the late 1960s and early 1970s, and from 1975 to 1977. Since 1977, most thinning in Alberta has been selective thinning by hand. Approximately 13,700 ha of pine, mainly lodgepole pine, have been thinned, principally by hand, in the interior of B.C.[2] All but 1000 ha of this total have been thinned since 1977. However, because of declining budgets, the lodgepole pine spacing effort has steadily declined since the peak year of 1980 when just over 4700 ha were treated. It is the intention here to outline and highlight some operational practices currently applied in Canada.

Chemical Thinning

Chemical thinning of lodgepole pine is not currently being carried out on an operational basis in Canada. Feasibility studies of chemical thinning were initiated in the early 1950s by Crossley (1956), who tested the efficacy of 2,4-D, 2,4,5-T, and ammonium sulphamate to thin young, very dense stands of lodgepole pine in Alberta. More recently, a number of chemical thinning trials have been conducted in B.C. During 1979, a study (SX 796020) was initiated to determine the dosage of monosodium methyl arsenate (MSMA) required to kill 25-year-old lodgepole pine trees (B.C. Ministry of Forests, 1981). In another study (E.P. 867), a system for injecting glyphosate-impregnated pellets into 25-year-old pine trees is under investigation (B.C. Ministry of Forests, 1981). Two years after applying Tordon 10k pellets (picloram), liquid picloram, Velpar "Gridball" pellets (hexazinone), and Hyvar XL (bromacil) in an 18-year-old lodgepole pine stand, Herring (1982) concluded that Hyvar XL was the most promising of the herbicides tested.

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[1] Personal communication with C.A. Dermott, Director, Reforestation & Reclamation Branch, Alberta Forest Service, Alberta Energy and Natural Resources, Edmonton, Alberta.

[2] Personal communication with M.H. Wyeth, Analyst, Siliviculture Branch, B.C. Ministry of Forests, Victoria, B.C.

Mechanical Thinning

Because of low costs per unit area relative to hand thinning, ease of supervision, reduced slash hazards, and the extensive area requiring treatment, mechanical strip or row thinning has attracted considerable interest in Canada. Mechanical thinning research in Canada was initiated by Crossley (1952). Since that time, a number of studies both in Canada (Bella, 1972; Bella and DeFranceschi, 1977, 1982; Herring, 1979, 1981) and in the United States (Lotan, 1967; Lynch, 1973; Tackle and Shearer, 1959) have tested a variety of equipment and treatment designs for strip thinning lodgepole pine. However, the economic advantages of strip thinning are still in doubt. Concerns about the survival of low branches in the cut strips, damage to the edge trees in residual strips and, owing to the lack of crop-tree selection, reduction in growth response to only half that observed after selective hand-thinning (Bella and DeFranceschi, 1982), have limited the current application of mechanical thinning in Canada. Of considerable current interest in B.C. is a combination of mechanical strip thinning followed by selective hand-thinning within the residual strips (Herring, 1981; Reid, Collins Nurseries Ltd., 1983). It is believed that this combination thinning may reduce by as much as half the cost of conventional hand spacing in dense stands. The ultimate success of this combination method will depend upon the development of equipment which removes narrow strips.

Selective Thinning

Although relatively more costly, selective thinning offers the greatest opportunity for controlling future stand volume and value through judicious crop-tree selection, control of growing stock levels, and stand sanitation. In B.C., juvenile spacing operations are carried out in accordance with regionally and provincially established guidelines (B.C. Ministry of Forests, 1979). These guidelines outline the biological and economic criteria to be considered in determining the thinning priority for individual stands. In general, selective thinning is conducted when stands are between 10 and 30 years old and 2 to 10 metres in height. At this stage of development, although better crop-tree selection is possible, lower live branches have been self-pruned, seedling ingress is complete, and pest activities are apparent, response potential is still high. Thinning is generally restricted to stands with densities between 1000 and 25,000 stems/ha; stands below 1000 stems will benefit little from spacing and the cost of hand spacing stands containing more than 25 000 stems is considered excessive. Higher priority is generally assigned to the more productive sites in anticipation of greater absolute responses. Stands with high levels of pest infections or infestations, with scattered clumpy stocking, or with average live crown percentages below 30% are normally avoided. In addition, to the foregoing biological considerations, higher priorities for thinning are usually assigned to stands which are: close to manufacturing centers, highly visible to the public, readily accessible, on flat to gently rolling topography, relatively free of slash or brush, and because of lower per-hectare overhead costs, large in area. In addition, some stands may be thinned to enhance non-timber values, such as forage production.

In the absence of substantive experimental evidence, post-thinning density standards have been developed mainly on the basis of the collective intuition of local silviculturists. Consequently, these spacing standards, which range from 2 to 3 metres for lodgepole pine in B.C., reflect the different philosophies, site and stand conditions, and management objectives in each region. Crop-tree selection is based upon crown position (i.e. dominant and co-dominant trees preferred), fullness of crown, vigor, crown color, bole straightness, and freedom from damage. Care is taken to ensure that crop trees are not damaged during thinning, live branches are removed from stumps, and cut trees are not left leaning or hinged (partially cut).

Precommercial spacing of lodgepole pine in Alberta is generally conducted according to criteria similar to those already outlined for B.C. For example, St. Regis (Alberta) Ltd.[3] usually delays spacing until the stands are about 15 years old and 2.5 to 3 metres tall. This permits better crop-tree selection because dominance is expressed, the vigor of late germinants is apparent, and freedom from pests is more evident. At the same time, delayed spacing minimizes the potential competition that results from further seedling ingress (Crossley, 1976; Johnstone, 1976). Thinning is generally restricted to stands containing more than 7400 stems/ha. A post-thinning density of about 2000 stems/ha is used although the selection of superior crop-trees is given a higher priority than is the strict adherence to spacing interval.

Although a wide variety of techniques (including hand-pulling, girdling, and hand and power tools) have been used, the majority of lodgepole pine stands in Canada have been selectively thinned with power saws. Production rates have varied considerably depending upon crew experience, access, stand and ground conditions, topography, and thinning implement used (Bella, 1974; Hedin, 1982). In B.C., a relatively uniform average production rate of 0.10 ha/hour per man has been observed[4] in stands containing less than 8300 stems/ha, but this rate declines rapidly with increasing stand density in stands denser than 8300 stems/ha.

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[3] Personal communication with J.C. Wright, Chief Forester, St. Regis (Alberta) Ltd., Hinton, Alberta.

[4] Britt, I.J. and J. Gallimore. 1983. A compilation of productivity studies on juvenile spacing. Unpublished report. Engineering Branch, B.C. Ministry of Forests. Victoria, B.C.

CONCLUDING REMARKS

North American research experience has shown that precommercial thinning can greatly enhance the merchantable yield and value of lodgepole pine stands. In many respects, the information from existing spacing and thinning studies is fragmented and of limited value for identifying the optimum stand management regimes for lodgepole pine. Although recent advances in computer simulation models may help compensate for this limited research experience, there is a lack of the high-quality, long-term growth and yield data required for adequately calibrating and testing these models. This situation prevails at a time when major commitments are being made to juvenile spacing and tree improvement programs, and when the planting of lodgepole pine is being undertaken at an ever-increasing rate.

Continued remeasurements and analysis of existing thinning studies will further contribute to the understanding of the management of lodgepole pine. Because of the pressing need for interim growth and yield estimates and because the amount of relevant data is limited, the establishment in western North America of a lodgepole pine growth and yield cooperative, in which existing data can be shared, appears to be timely. At the same time, several new research initiatives are necessary for the further development and refinement of our silvicultural prescriptions and our planning and decision-making processes. For example, the actual yield gains realized in operationally managed stands are rarely as large as those indicated by research results. Therefore, it is necessary to monitor operationally treated stands to determine the magnitude of this "falldown."

The current trends in British Columbia indicate a declining reliance on natural regeneration and an increase in the establishment of lodgepole pine plantations, and in the eventual use of genetically improved planting stock. Very little information is available on the effects and interactions that initial espacement and subsequent thinning in plantations have on the growth, yield, and value of lodgepole pine. As our management of lodgepole intensifies, there is a growing need to establish process-oriented research, not only to help improve our fundamental understanding of tree growth and stand dynamics, but also to complement and help explain inconsistencies in our empirical studies. Furthermore, in the future we will require information on environmental-genotype interactions and the effects of our silvicultural treatments on price/cost-size relationships and wood quality. Finally, because thinning may substantially alter the risks associated with managing lodgepole pine, quantitative risk factors are urgently needed for incorporation into planning models and stand-management regimes.

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GROWTH AND YIELD OF LODGEPOLE PINE

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ABSTRACT

Stand growth and yield were estimated using whole stand growth models developed for managed stands in Colorado and southern Wyoming and for managed and unmanaged stands in Montana and Idaho. Potential production is estimated for various combinations of stand density, site quality, rotation age, and thinning schedules. Merchantable cubic volume production per unit area is maximized at relatively high stand densities. Volume production substantially declines when managed stand density is reduced. The optimum stand density is related to site quality.

Whether potential levels of production can be achieved depends on how much money can be invested in thinning and the importance, relative to timber values, of other resource values such as water yield, forage production, and recreation. In addition, stand densities may have to be maintained below optimum levels to minimize insect and disease problems. For most management considerations, cutting cycles of 30 years seem most feasible. Applicability of the models to other geographical areas is discussed.

INTRODUCTION

Lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) has historically been a relatively neglected species in terms of its potential for management. But in recent years its widespread occurrence as a timber type and increasing concerns over timber supplies have worked to increase interest in its growth and yield characteristics and management potential.

The silvical characteristics of lodgepole pine and their general effect on growth and yield have been well-established. Clements (1910) and Mason (1915) described the striking effects of excessive stocking on growth of individual trees and stands, in contrast to growth and size potential when densities are favorable. Although it is interesting to know of the extreme effects of overstocking or of the maximum size of individual trees, managers are more interested in the stand dynamics that produce a given condition. They need to know what yield can be expected from different lodgepole pine stands under different forms and intensities of management.

It has been only in the last 20-30 years that the growth and yield of lodgepole pine has been quantified in terms of the interacting effects of site, stand density, and age. From 1950 to the early 1970s, several studies established the nature of the growth and yield relationships involved with unmanaged lodgepole pine stands (Smithers, 1961; Ackerman, 1962; Dahms, 1964; Alexander and others, 1967; Johnstone, 1976). Other studies examined the early effects of different types of thinning in stands of different age, site quality, and stand density (Alexander, 1956, 1960, 1965; Smithers, 1957, 1961; Daniel and Barnes, 1958; Barrett, 1961; Dahms, 1967, 1971, 1973). Despite these advances, the extension of this information to widely applicable variable density yield tables for managed stands was not accomplished. Research efforts early in this period were limited to the sheer weight of calculations needed to reduce data and account for the interactions affecting tree and stand growth parameters, and by the scarcity of data on stand development. Although records on permanent plots are sometimes still inadequate (Dahms, 1983), we are now in a somewhat better position – largely by virtue of remeasurement data from studies established 10-30 years ago and access to computers and software for performing calculations.

Thus, we now have the capability to develop yield tables or forecasts for many combinations of age, site quality, and stand density – for both managed and unmanaged lodgepole pine stands. This is shown by the several computerized growth and yield or stand development models currently operational or in development (Stage, 1973; Edminster, 1978; Dahms, 1983; Cole, 1983). Although varying in their geographic applicability, all of the recent growth and yield models embody growth functions for the three major components of volume and value yield – height, diameter, and basal area – and some have functions for other tree and stand characteristics involved in stand development. Each model also addresses, to one degree or another, mortality due to competition, age, and other factors.

Estimates of future growth and yield of lodgepole pine stands have often been made by reference to normal yield tables or by reference to stock tables of similar stands. Both approaches have serious limitations. The normal yield approach is not applicable to overstocked or understocked stands, and use of stock tables is limited by the accuracy of expectations on future height and density of the subject stand. Stand growth models, however, address these problems and provide better estimates of future growth and yield of even-aged lodgepole pine stands. Stand growth models also provide an efficient way to compare the growth and yield effects of various alternative thinning regimes with the option of no management.

Our purpose in this paper is to present and compare growth and yield results of two versions of an earlier-developed stand projection program (Myers and others, 1971), refined by the authors for different growth and management situations of the central and northern Rocky Mountain areas of the United States. The models are compared over varying levels of site quality, stand density, management intensity, and rotation lengths appropriate to even-aged management of lodgepole pine. Managed-stand comparisons follow the format used by Alexander and Edminster (1981) for evaluating effects of repeated thinning of lodgepole pine stands of the central Rockies. Selected comparisons of model performance are also made with yields of stands from other regions.

DEVELOPMENT OF MODELS

The stand growth models compared in this paper are refinements of a computer model (LPMIST) developed by Myers and others (1971) for managed stand simulations of thinning at different intervals and intensities. One of the stand models is also applicable to unmanaged stands. Relationships from this model, LP STAND GRO (Cole and Jensen, 1982; Cole, 1983), were recently incorporated into a species-specific subroutine of program RMYLD (Edminster, 1978). This subroutine, LPPIM (*l*odge*p*ole *p*ine in *I*daho and *M*ontana), is referred to as the "northern" model throughout the remainder of this paper. The other stand model is essentially the refined version of LPMIST developed by Edminster (1978). It is a managed-stand growth model, likewise incorporated into RMYLD as a separate subroutine called LPMIST. In the discussion that follows, this model is referred to as the "central" model. It was developed from managed stands in Colorado and southern Wyoming. For purposes of model development, managed stands were defined as stands which had been thinned and were being maintained under controlled stand density for more than one 10-year measurement period.

In both models, the whole stand is the primary model unit, as characterized by average values. The equations for the central model, upon which growth and yield estimates are based, are given in the program listing in the appendix of Myers and others (1971). The central model projects stand development by consecutive, 10-year periods and includes relationships to project average stand diameter, average dominant and codominant height, and periodic mortality for stands not infested by dwarf mistletoe (*Arceuthobium americanum* Nutt. ex Engel.). Separate relationships express effects of dwarf mistletoe and changes in the intensity of infestation. Stand volume equations are used to compute total cubic-foot volume per unit area, and factors are computed to convert to merchantable volumes.

The northern model contains relationships for average diameter growth (Cole and Stage, 1972), periodic mortality, crown competition factor (Krajicek and others, 1961), crown development (Cole and Jensen, 1982), cubic stand volume (Cole, 1971), and merchantable volume conversion (Cole, 1979). Both models use the same dwarf mistletoe relationships and prediction equations to estimate the effects of differing intensities of thinning from above and below on average diameter, height, and number of trees retained per unit area.

Both models use the thinning routines developed by Myers (1967). Myers' routine for thinning from below utilizes a growing stock level (GSL) criterion for determining the intensity of thinning. GSL is defined as the basal area of the stand when the average stand diameter reaches 25.4 cm. Stands having basal areas greater than a chosen GSL and average stand diameters greater than 25.4 cm will have basal areas in square meters per hectare, following thinning, equal to the GSL chosen for thinning intensity. When the average stand diameter is less than 25.4 cm, however, residual stand basal areas will always be less than the GSL. To avoid the implication that basal area levels following thinning are equal to the GSL chosen for the thinning simulation, we have chosen to call the thinning intensity criterion, used in the northern and central models, a growing stock index (GSI).

STAND CONDITIONS SIMULATED

Yield simulations were made for the following range of stand conditions, assumptions, and management controls:

1. Site indexes at total age of 100 years of 15.2, 18.3, 21.3, and 24.4 meters (50, 60, 70, and 80 feet).
2. Stand densities at age 20 years of 2,965, 4,942, 9,884, and 19,768 trees per hectare (1,200, 2,000, 4,000, and 8,000 trees per acre).
3. Stands are assumed to be free of dwarf mistletoe and no catastrophic mortality occurs.
4. All thinning simulations begin with thinning from below at 20 years of age.
5. Single precommercial thinnings of the various stand densities tested are made to GSI 13.8, leaving approximately 890 to 1,038 trees/ha (360 to 420 trees/acre) for development to age 120 years.
6. Simulations of repeated thinnings are made on 10-, 20-, and 30-year thinning cycles to growing stock indexes (GSI's) of 9.2, 13.8, 18.4, 23.0, 27.5, 32.1, and 36.7 m^2/ha (40, 60, 80, 100, 120, 140, and 160 ft^2/acre, respectively), with initial and subsequent entries made to the same GSI.
7. Rotation lengths of 80 and 120 years, clearcut at rotation.
8. Minimum d.b.h. for inclusion in merchantable cubic volume is 11.7 cm (4.6 inches) for the northern model and 15.2 cm (6.0 inches) for the central model. A minimum top diameter inside bark of 10.2 cm (4.0 inches) is used for all cubic volume determinations.
9. All thinnings are made as scheduled even though all could be precommercial.

GROWTH AND YIELD RESULTS

Average Stand Diameter Growth

The average diameter of trees at harvest or at intermediate cutting is important to managing tree-size and quality. As with most species lending themselves to even-aged management, diameter growth of lodgepole pine is maximized at low stand densities. But stand densities where mean diameter growth is greatest are too low for maximum volume yield per unit area. Thus, determination of some "optimum" density necessarily involves a trade-off between size and stand volume objectives.

Effects of stand density on average stand diameter were examined with the northern and central models – for different site qualities and management intensities. Diameter growth of lodgepole pine stands was found to be negatively correlated with stand density, as represented by crown competition factor or stand basal area, but positively correlated with site index (tables 1-4). Although precommercial thinning to relieve overstocking results in increased diameter growth, cutting cycles and intensities of thinning have relatively little further effect on diameter growth. Thinning intensity and frequency, however, do influence the average stand diameter because thinnings from below remove smaller trees, thus elevating the average of residual trees.

In unmanaged stands of site index 15.2 m (50 ft) and initial stand densities of 19,768 trees/ha (8,000 trees/acre), trees can only be expected to reach average stand diameters of about 7.6 cm (3.0 inches) at 80 years and 10.7 cm (4.2 inches) at 120 years (table 1). Even on significantly better sites, high stand densities limit average stand diameters. For example, on site index 24.4 m (80 ft) lands, stand densities of 19,768 trees/ha (8,000 trees/acre) at 20 years result in average stand diameters of only 9.1 cm (3.6 inches) at 80 years and 13.0 cm (5.1 inches) at 120 years, while 2,965 trees/ha (1,200 trees/acre) will develop to about 17.0 cm (6.7 inches) at 80 years and 21.1 cm (8.3 inches) at 120 years (table 4).

Thinning consolidates stand growth on fewer and larger trees. Tables 5-8 summarize how a single precommercial thinning with the northern model affects average stand diameter and other growth and yield characteristics as the stand develops to age 120 years.

When initial stand densities from 4,942 to 19,768 trees/ha (2,000 to 8,000 trees/acre) are precommercially thinned at age 20 years to a GSI of 13.8, average stand diameters without further thinning will reach 18.5 cm (7.3 inches) at age 80 years and 22.6 cm (8.9 inches) at age 120 years, for site index 15.2 m (50 ft)(table 5). This amounts to an increase in the average stand diameters, from the unmanaged condition, of 10.9 cm (4.3 inches) at 80 years and 11.9 cm (4.7 inches) at 120 years (fig. 1). On site index 24.4 m (80 ft) lands, single precommercial thinnings to GSI 13.8 result in average stand diameters of 22.9 to 23.6 cm (9.0 to 9.3 inches) at 80 years and 27.7 to 28.7 cm (10.9 to 11.3 inches) at 120 years (table 8). This is an increase over the unmanaged condition of up to 16.0 cm (6.3 inches) at 80 years and 18.0 cm (7.1 inches) at 120 years (fig. 2).

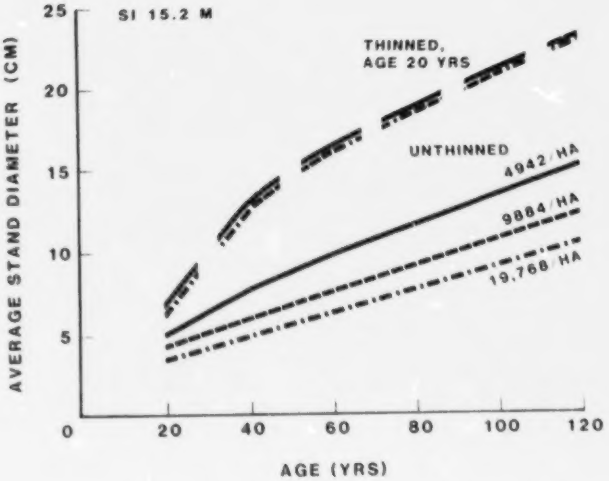

Figure 1. – Northern model estimates of effect of precommercial thinning at 20 years to GSI 13.8 on average stand diameter/age relationship; site index 15.2 m lands in Idaho and Montana.

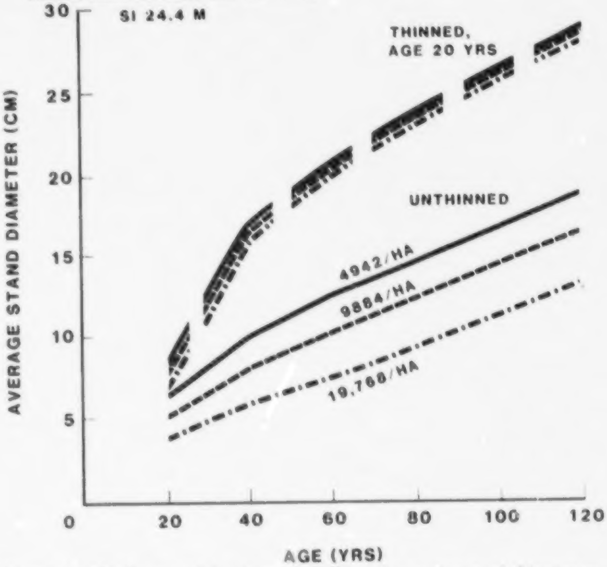

Figure 2. – Northern model estimates of effect of precommercial thinning at 20 years to GSI 13.8 on average stand diameter/age relationship; site index 24.4 m lands in Idaho and Montana.

The northern model was used to examine the effect of repeated thinning on average stand diameter in comparison to a single precommercial thinning and the unmanaged condition. Beyond 40 years of age, most of the increase in average stand diameter due to repeated thinning is due to the removal of smaller trees at each thinning cycle, thus elevating average stand diameter (fig. 3). Tables 9 and 10 summarize the effects of repeated thinning with the northern model on average stand diameter relative to stand age, thinning intensity, and site index for a 20-year cutting cycle. Average stand diameters are seen to reach 16.0 cm (6.3 inches) to 39.9 cm (15.7 inches)

Table 1.—Northern model estimates of unmanaged stand development of different stand densities at age 20 years on site index 15.2 m lands in Idaho and Montana.

Age	Trees/ha	Average stand diameter	Basal area	Average dom. height	Total volume	Total volume MAI	Merch. volume ratio
(years)		(cm)	(m^2/ha)	(m)	(m^3/ha)	(m^3/ha/yr)	
20	19,768	2.8	11.5	2.4	11.9	0.6	--
40	15,762	4.6	25.7	4.9	58.7	1.4	--
60	10,077	6.1	29.4	7.3	100.1	1.7	--
80	6,397	7.6	29.2	9.8	131.5	1.6	--
100	4,334	9.1	28.5	11.9	156.0	1.6	--
120	3,113	10.7	27.8	13.7	177.0	1.5	--
20	9,884	3.3	8.5	3.0	9.8	0.5	--
40	8,248	5.8	22.0	5.8	56.7	1.4	--
60	6,024	7.6	27.5	8.2	103.6	1.7	--
80	4,233	9.1	27.8	10.7	135.0	1.7	--
100	3,079	10.7	27.5	12.5	160.9	1.6	--
120	2,325	12.4	28.2	14.6	190.3	1.6	0.51
20	4,942	4.3	7.3	4.0	11.2	0.6	--
40	4,124	7.6	18.8	6.7	56.7	1.4	--
60	3,385	9.7	24.8	9.1	105.0	1.7	--
80	2,607	11.7	28.0	11.6	149.7	1.9	0.38
100	1,987	13.5	28.2	13.7	179.1	1.8	0.62
120	1,544	15.2	28.2	15.5	203.6	1.7	0.74
20	2,965	4.8	5.5	4.9	9.8	0.5	--
40	2,473	9.1	16.3	7.9	56.7	1.4	--
60	2,105	11.7	22.5	10.4	107.1	1.8	0.38
80	1,737	13.7	25.7	12.5	150.4	1.9	0.64
100	1,401	15.7	27.3	14.6	186.8	1.9	0.77
120	1,124	17.8	28.0	16.8	215.5	1.8	0.83

Table 2.—Northern model estimates of unmanaged stand development of different stand densities at age 20 years on site index 18.3 m lands in Idaho and Montana

Age	Trees/ha	Average stand diameter	Basal area	Average dom. height	Total volume	Total volume MAI	Merch. volume ratio
(years)		(cm)	(m^2/ha)	(m)	(m^3/ha)	(m^3/ha/yr)	
20	19,768	3.0	14.5	2.7	16.1	0.8	--
40	16,501	4.8	30.1	6.1	85.4	2.6	--
60	12,810	6.4	40.6	9.5	175.6	2.9	--
80	9,041	7.9	44.1	12.2	249.1	3.1	--
100	6,395	9.4	44.3	14.6	302.3	3.0	--
120	4,687	10.9	44.0	16.8	342.9	2.9	--
20	9,884	3.8	11.3	3.7	16.8	0.9	--
40	8,248	6.4	26.2	7.3	88.2	2.2	--
60	6,837	8.1	35.6	10.7	172.8	2.9	--
80	5,416	9.7	39.7	13.4	245.6	3.1	--
100	4,216	11.2	41.3	15.9	304.4	3.0	--
120	3,301	12.7	41.8	18.0	349.9	2.9	0.54
20	4,942	4.8	9.0	4.6	16.8	0.9	--
40	4,124	8.4	22.7	8.5	88.9	2.2	--
60	3,442	10.7	30.8	11.6	166.5	2.8	--
80	2,874	12.7	36.5	14.6	245.6	3.1	0.54
100	2,399	14.2	38.1	17.1	300.9	3.0	0.68
120	2,006	15.8	39.0	19.2	347.8	2.9	0.77
20	2,965	5.3	6.7	5.5	14.7	0.7	--
40	2,474	9.9	19.1	9.8	84.7	2.1	--
60	2,177	12.7	27.6	12.8	164.4	2.7	0.43
80	1,952	14.7	33.3	15.5	242.8	3.0	0.72
100	1,697	16.5	36.3	18.3	307.9	3.1	0.79
120	1,463	18.0	37.4	20.4	353.4	2.9	0.84

Table 3.—Northern model estimates of unmanaged stand development of different stand densities at age 20 years on site index 21.3 m lands in Idaho and Montana

Age	Trees/ha	Average stand diameter	Basal area	Average dom. height	Total volume	Total volume MAI	Merch. volume ratio
(years)		(cm)	(m^2/ha)	(m)	(m^3/ha)	(m^3/ha/yr)	
20	19,768	3.3	17.0	3.4	24.5	1.2	--
40	16,239	5.6	39.7	7.3	133.6	3.3	--
60	11,243	7.1	44.8	11.0	288.8	3.8	--
80	7,697	8.6	45.0	14.3	300.9	3.8	--
100	5,448	10.2	44.5	17.1	355.5	3.6	--
120	4,082	11.7	43.9	19.5	398.1	3.3	0.39
20	9,884	4.3	14.5	4.9	30.8	1.5	--
40	8,248	7.1	32.8	9.1	137.1	3.4	--
60	6,511	9.1	42.7	12.8	254.7	4.3	--
80	4,836	10.7	43.2	16.2	324.0	4.1	--
100	3,682	12.2	42.9	18.9	379.2	3.8	0.48
120	2,879	13.7	42.5	21.3	422.6	3.5	0.64
20	4,942	5.3	11.0	5.8	28.0	1.4	--
40	4,124	9.1	27.1	10.1	127.4	3.2	--
60	3,442	11.4	35.4	14.0	228.8	3.8	0.34
80	2,851	13.5	40.6	17.4	326.1	4.1	0.62
100	2,303	15.5	43.4	20.1	406.5	4.1	0.76
120	1,858	17.3	43.6	22.6	456.2	3.8	0.82
20	2,965	5.8	8.0	6.4	21.7	1.1	--
40	2,473	10.7	22.0	11.0	112.7	2.8	--
60	2,157	13.5	30.8	14.9	211.3	3.5	0.62
80	1,890	15.8	36.7	18.0	310.7	3.9	0.76
100	1,609	17.8	39.9	21.0	390.4	3.9	0.83
120	1,349	19.8	41.6	23.2	452.7	3.8	0.87

Table 4.—Northern model estimates of unmanaged stand development of different stand densities at age 20 years on site index 24.4 m lands in Idaho and Montana

Age	Trees/ha	Average stand diameter	Basal area	Average dom. height	Total volume	Total volume MAI	Merch. volume ratio
(years)		(cm)	(m^2/ha)	(m)	(m^3/ha)	(m^3/ha/yr)	
20	19,768	3.8	19.7	3.7	31.5	1.6	--
40	15,874	5.8	42.5	7.9	156.7	3.9	--
60	10,662	7.4	45.5	12.2	260.3	4.3	--
80	7,285	9.1	47.8	16.2	359.0	4.5	--
100	5,085	10.9	47.8	19.2	428.9	4.3	--
120	3,664	13.0	48.2	22.0	494.0	4.1	0.57
20	9,884	5.1	20.0	5.8	52.5	2.6	--
40	8,201	7.9	39.9	10.4	190.3	4.8	--
60	6,024	9.9	46.4	14.6	316.3	5.3	--
80	4,302	11.9	48.2	18.3	413.5	5.2	0.44
100	3,146	14.0	48.2	21.6	486.3	4.9	0.67
120	2,370	16.0	47.7	24.1	538.8	4.5	0.78
20	4,942	6.1	14.5	7.0	45.5	2.3	--
40	4,124	9.7	30.1	11.9	164.4	4.1	--
60	3,440	12.2	40.2	16.2	301.6	5.0	0.47
80	2,745	14.2	43.6	19.8	405.1	5.1	0.68
100	2,172	16.3	45.0	23.2	486.3	4.9	0.79
120	1,727	18.3	45.5	25.6	544.4	4.5	0.84
20	2,965	6.6	10.1	7.0	31.5	1.6	--
40	2,473	11.7	26.6	11.9	146.9	3.7	0.39
60	2,125	14.5	34.9	16.5	266.6	4.4	0.70
80	1,811	17.0	41.1	20.1	386.9	4.8	0.81
100	1,497	19.1	42.7	23.2	464.6	4.7	0.86
120	1,236	21.1	43.2	25.9	522.7	4.4	0.89

Table 5.—Northern model estimates of effect of a single precommercial thinning to GSI 13.8 at age 20 years in stands of different densities on site index 15.2 m lands in Idaho and Montana

Age	Trees/ha	Average stand diameter	Basal area	Average dom. height	Total volume	Total volume MAI	Merch. volume ratio
(years)		(cm)	(m^2/ha)	(m)	(m^3/ha)	(m^3/ha/yr)	
20	19,768	2.8	12.2	2.4	11.9	0.6	--
20	1,028	4.8	1.8	3.7	0.7	--	--
40	1,013	12.7	12.9	7.0	39.9	1.3	0.53
60	946	16.0	19.1	9.5	81.9	1.6	0.77
80	843	18.5	22.7	11.9	124.6	1.7	0.85
100	729	20.6	24.3	14.0	156.7	1.7	0.88
120	623	22.6	25.0	15.9	184.0	1.6	0.90
20	9,884	3.3	8.5	3.1	9.8	0.5	--
20	1,025	5.1	2.1	4.0	1.4	--	--
40	1,008	12.7	12.9	7.3	41.3	1.3	0.53
60	941	16.0	18.8	9.8	85.4	1.6	0.78
80	838	18.5	22.7	12.2	127.4	1.7	0.85
100	724	20.6	24.1	14.3	158.8	1.7	0.89
120	618	22.6	24.8	16.2	186.1	1.6	0.91
20	4,942	4.3	7.4	4.0	11.2	0.6	--
20	998	5.8	2.8	4.6	3.5	--	--
40	981	13.0	12.9	7.9	45.5	1.3	0.55
60	917	16.3	19.1	10.4	90.3	1.6	0.79
80	818	18.8	22.8	12.8	132.9	1.8	0.86
100	709	20.8	24.1	14.9	165.8	1.7	0.89
120	608	23.0	25.0	16.8	193.1	1.7	0.91

Table 6.—Northern model estimates of effect of a single precommercial thinning to GSI 13.8 at age 20 years in stands of different densities on site index 18.3 m lands in Idaho and Montana

Age	Trees/ha	Average stand diameter	Basal area	Average dom. height	Total volume	Total volume MAI	Merch. volume ratio
(years)		(cm)	(m^2/ha)	(m)	(m^3/ha)	(m^3/ha/yr)	
20	19,768	3.1	14.5	2.7	16.1	0.8	--
20	1,021	5.3	2.3	4.0	2.1	--	--
40	1,013	14.0	15.6	8.8	63.0	1.9	0.66
60	976	17.3	23.0	12.2	127.4	2.4	0.82
80	917	19.8	28.2	14.9	195.2	2.6	0.87
100	840	21.8	31.5	17.4	254.7	2.7	0.90
120	756	23.9	33.8	19.5	307.9	2.7	0.91
20	9,884	3.8	11.3	3.7	16.8	0.9	--
20	998	5.8	2.6	4.6	3.5	--	--
40	991	14.0	15.2	9.5	65.8	2.0	0.66
60	956	17.3	22.5	12.8	131.6	2.4	0.82
80	899	19.8	27.8	15.5	199.4	2.7	0.87
100	828	21.8	31.0	18.0	259.6	2.7	0.90
120	746	23.9	33.5	20.1	312.8	2.7	0.91
20	4,942	4.8	9.0	4.6	16.8	0.9	--
20	956	6.6	3.2	5.2	5.6	--	--
40	949	14.5	15.6	10.1	71.4	2.1	0.70
60	914	17.8	22.7	13.1	138.5	2.5	0.83
80	860	20.3	27.8	16.2	207.1	2.7	0.88
100	788	22.4	31.0	18.6	265.9	2.8	0.90
120	712	24.4	33.3	20.7	319.1	2.8	0.92

Table 7.—Northern model estimates of effect of a single precommercial thinning to GSI 13.8 at age 20 years in stands of different densities on site index 21.3 m lands in Idaho and Montana

Age	Trees/ha	Average stand diameter	Basal area	Average dom. height	Total volume	Total volume MAI	Merch. volume ratio
(years)		(cm)	(m^2/ha)	(m)	(m^3/ha)	(m^3/ha/yr)	
20	19,768	3.6	19.7	3.4	28.7	1.4	--
20	986	6.1	3.0	4.6	4.2	--	--
40	976	15.2	17.9	10.1	81.2	2.6	0.74
60	932	18.8	25.9	13.7	163.7	3.1	0.86
80	860	21.6	31.5	17.1	249.1	3.4	0.90
100	771	23.9	34.4	19.8	319.1	3.4	0.91
120	680	25.9	35.8	22.3	370.9	3.3	0.93
20	9,884	4.3	14.3	4.9	30.8	1.5	--
20	956	6.6	3.2	5.8	7.0	--	--
40	946	15.2	17.2	11.3	88.9	2.8	0.74
60	904	18.8	25.0	14.9	174.9	3.3	0.86
80	840	21.6	30.8	18.3	262.4	3.6	0.90
100	759	23.9	34.0	21.0	334.5	3.6	0.92
120	670	25.9	35.4	23.5	386.9	3.4	0.93
20	4,942	5.3	11.0	5.8	28.0	1.4	--
20	924	7.1	3.7	6.4	9.1	--	--
40	914	15.5	17.2	11.9	93.1	2.8	0.76
60	877	19.1	25.0	15.5	180.5	3.3	0.86
80	813	21.8	30.5	18.9	267.3	3.6	0.90
100	734	24.1	33.5	21.6	339.4	3.6	0.92
120	650	26.2	34.9	24.1	392.5	3.4	0.93

Table 8.—Northern model estimates of effect of a single precommercial thinning to GSI 13.8 at age 20 years in stands of different densities on site index 24.4 m lands in Idaho and Montana

Age	Trees/ha	Average stand diameter	Basal area	Average dom. height	Total volume	Total volume MAI	Merch. volume ratio
(years)		(cm)	(m^2/ha)	(m)	(m^3/ha)	(m^3/ha/yr)	
20	19,768	4.0	25.7	4.0	45.5	2.3	--
20	941	6.9	3.4	5.2	6.3	--	--
40	932	16.3	19.3	11.0	97.3	3.4	0.78
60	885	20.1	28.0	15.2	198.7	4.0	0.88
80	808	22.9	33.1	19.2	294.6	4.2	0.91
100	717	25.4	36.3	22.3	377.1	4.2	0.92
120	620	27.7	37.4	25.0	433.8	4.0	0.93
20	9,884	5.1	20.0	5.8	52.5	2.6	--
20	892	7.6	4.1	7.0	10.5	--	--
40	880	16.5	18.8	12.5	108.5	3.8	0.80
60	838	20.3	27.1	17.1	213.4	4.3	0.88
80	768	23.4	33.1	20.7	317.7	4.5	0.91
100	682	25.9	36.0	23.8	400.9	4.4	0.93
120	591	28.2	37.0	26.5	456.2	4.2	0.94
20	4,942	6.1	14.5	7.0	45.5	2.3	--
20	862	8.1	4.4	7.9	14.0	--	--
40	850	16.8	18.8	13.4	116.2	3.7	0.81
60	808	20.8	27.6	17.7	228.1	4.3	0.89
80	739	23.6	32.4	21.6	325.4	4.5	0.91
100	657	26.2	35.4	24.7	408.6	4.4	0.93
120	573	28.7	37.2	27.4	474.4	4.2	0.94

Table 9.—Northern model estimates of stand diameter, in centimeters, in relation to age and growing stock index after thinning at 20-year intervals, for site indexes of 15.2 and 18.3 m in Idaho and Montana

Age	Growing stock index						
	9.2	13.8	18.4	23.0	27.5	32.1	36.7
-years-	cm						
	Site Index 15.2 m						
20	5.1	5.1	5.1	5.1	5.1	5.1	5.1
20	6.9	6.6	6.4	6.1	5.8	5.8	5.6
30	13.7	11.7	10.7	9.7	9.1	8.6	8.4
40	16.5	14.2	12.7	11.7	10.9	10.4	10.2
40	18.5	15.7	14.0	12.7	11.9	11.2	10.7
50	21.8	18.3	16.3	14.7	13.7	12.7	12.2
60	24.1	20.3	18.0	16.3	15.2	14.0	13.5
60	25.7	21.6	19.1	17.0	15.7	14.2	13.7
70	28.4	23.6	20.8	18.5	17.0	15.5	15.0
80	30.7	25.4	22.4	19.8	18.3	16.8	16.0
80	32.5	26.7	23.4	20.3	18.5	16.8	16.0
90	35.1	28.4	24.9	21.6	19.8	17.8	17.0
100	37.3	30.2	26.2	22.9	20.8	18.8	18.0
100	39.1	31.8	27.2	23.4	20.8	18.8	18.0
110	41.7	33.5	28.7	24.6	21.8	19.8	19.1
120	43.9	35.3	30.0	25.9	22.9	20.8	20.1
	Site Index 18.3 m						
20	5.6	5.6	5.6	5.6	5.6	5.6	5.6
20	7.6	7.1	6.9	6.6	6.4	6.4	6.1
30	14.7	12.7	11.4	10.7	9.9	9.4	8.9
40	17.8	15.2	13.7	12.7	11.9	11.2	10.9
40	19.8	16.8	15.0	14.0	13.0	12.2	11.7
50	23.4	19.6	17.5	16.0	14.7	14.0	13.2
60	26.2	21.8	19.3	17.8	16.3	15.5	14.5
60	27.9	23.4	20.6	18.8	17.0	16.3	15.0
70	31.2	25.7	22.4	20.3	18.5	17.5	16.3
80	33.8	27.4	23.9	21.8	19.8	18.8	17.3
80	35.6	29.0	25.1	22.9	20.6	19.3	17.8
90	38.6	31.2	26.9	24.4	21.8	20.6	18.8
100	41.1	33.0	28.4	25.7	23.1	21.6	19.8
100	43.2	34.5	30.0	26.7	23.9	22.1	20.3
110	46.2	36.6	31.5	27.9	25.1	23.1	21.3
120	48.8	38.6	33.0	29.2	26.2	24.1	22.4

Table 10.—Northern model estimates of stand diameter, in centimeters, in relation to age and growing stock index after thinning at 20-year intervals, for site indexes of 21.3 and 24.4 m in Idaho and Montana

	Growing stock index						
Age	9.2	13.8	18.4	23.0	27.5	32.1	36.7
-years-				cm			
				Site Index 21.3 m			
20	6.1	6.1	6.1	6.1	6.1	6.1	6.1
20	8.4	7.9	7.4	7.4	7.1	6.9	6.9
30	16.0	13.7	12.2	11.4	10.7	10.2	9.9
40	19.1	16.5	14.7	13.7	12.7	12.2	11.9
40	21.3	18.0	16.3	15.0	14.0	13.2	12.7
50	25.4	21.1	18.8	17.3	16.0	15.0	14.5
60	28.2	23.4	20.8	19.1	17.5	16.5	15.7
60	30.2	24.9	22.1	20.1	18.5	17.3	16.3
70	33.8	27.4	24.1	21.8	20.1	18.8	17.5
80	36.6	29.5	25.9	23.4	21.6	20.1	18.8
80	38.6	31.2	27.4	24.4	22.6	20.8	19.3
90	42.2	33.8	29.5	25.9	23.9	22.1	20.6
100	45.0	35.8	31.2	27.4	25.1	23.4	21.6
100	47.0	37.6	32.8	28.7	26.2	24.1	22.1
110	50.3	39.9	34.5	30.2	27.4	25.4	23.1
120	53.3	42.2	36.3	31.8	28.7	26.4	24.1
				Site Index 24.4 m			
20	6.9	6.9	6.9	6.9	6.9	6.9	6.9
20	9.4	8.9	8.4	8.1	7.9	7.9	7.6
30	17.3	14.7	13.5	12.4	11.7	11.2	10.7
40	20.6	17.5	16.0	14.7	13.7	13.2	12.4
40	23.1	19.3	17.5	16.0	15.0	14.2	13.5
50	27.4	22.6	20.3	18.5	17.0	16.3	15.2
60	30.5	25.1	22.4	20.3	18.8	17.8	16.8
60	32.5	26.9	23.6	21.6	19.8	18.5	17.5
70	36.6	29.7	25.9	23.6	21.6	20.1	19.1
80	39.9	32.0	27.9	25.1	23.1	21.6	20.3
80	41.9	33.8	29.5	26.4	24.1	22.4	20.8
90	45.7	36.6	31.8	28.2	25.7	23.6	22.1
100	49.0	38.9	33.5	29.7	27.2	24.9	23.4
100	51.3	40.6	35.1	31.0	28.4	25.7	23.9
110	55.1	43.4	37.1	32.8	30.0	26.9	25.1
120	58.4	45.7	39.1	34.3	31.2	28.2	26.2

Table 11.–Central model estimates of average stand diameter, in centimeters, in relation to age and growing stock index after thinning at 20-year intervals, for site indexes of 15.2 and 18.3 m in Colorado and southern Wyoming

	Growing stock index						
Age	9.2	13.8	18.4	23.0	27.5	32.1	36.7
-years-				cm			
				Site Index 15.2 m			
20	5.1	5.1	5.1	5.1	5.1	5.1	5.1
20	6.9	6.6	6.4	6.1	5.8	5.8	5.6
30	11.2	10.4	9.9	9.4	9.1	8.9	8.4
40	14.2	13.2	12.4	11.7	11.2	10.9	10.4
40	15.5	14.5	13.7	12.7	12.2	11.9	11.2
50	18.5	17.0	16.0	14.7	14.0	13.7	12.7
60	21.3	19.3	18.0	16.5	15.5	15.0	14.0
60	22.9	20.6	19.3	17.5	16.5	15.7	14.7
70	25.7	22.9	21.3	19.3	18.0	17.0	16.0
80	28.4	24.9	23.1	20.8	19.3	18.3	17.0
80	30.2	26.2	24.4	21.8	20.3	19.1	17.8
90	33.3	28.4	26.4	23.4	21.6	20.3	18.8
100	36.1	30.7	28.2	24.9	22.9	21.3	19.8
100	38.1	32.5	29.7	26.2	23.9	22.4	20.6
110	41.1	35.1	31.8	27.7	25.1	23.4	21.6
120	44.2	37.3	33.5	29.2	26.4	24.4	22.6
				Site Index 18.3 m			
20	5.6	5.6	5.6	5.6	5.6	5.6	5.6
20	7.6	7.1	6.9	6.6	6.4	6.4	6.1
30	12.2	11.2	10.7	10.2	9.7	9.4	9.1
40	15.5	14.2	13.5	12.7	11.9	11.7	11.4
40	17.0	15.5	14.7	14.0	13.0	12.7	12.2
50	20.3	18.5	17.3	16.3	15.2	14.7	14.0
60	23.4	21.1	19.6	18.3	17.0	16.3	15.5
60	24.9	22.6	20.8	19.6	18.0	17.3	16.3
70	28.2	25.4	23.1	21.6	19.8	19.1	17.8
80	31.2	27.9	25.1	23.4	21.3	20.6	19.1
80	33.0	29.7	26.7	24.6	22.4	21.6	19.8
90	36.3	32.5	29.0	26.7	24.1	23.1	21.3
100	39.6	35.1	31.0	28.4	25.7	24.4	22.6
100	41.7	36.8	32.8	30.0	26.9	25.7	23.6
110	45.2	39.9	35.3	32.0	28.7	27.2	24.9
120	48.8	42.7	37.6	34.0	30.5	28.7	26.2

Table 12.—Central model estimates of average stand diameter, in centimeters, in relation to age and growing stock index after thinning at 20-year intervals, for site indexes of 21.3 and 24.4 m in Colorado and southern Wyoming

Age	Growing stock index						
	9.2	13.8	18.4	23.0	27.5	32.1	36.7
-years-	cm						
	Site Index 21.3 m						
20	6.1	6.1	6.1	6.1	6.1	6.1	6.1
20	8.4	7.9	7.4	7.4	7.1	6.9	6.9
30	13.2	12.2	11.4	11.2	10.7	10.2	10.2
40	16.8	15.5	14.5	14.0	13.2	12.7	12.4
40	18.3	17.0	15.7	15.2	14.5	14.0	13.5
50	22.1	20.3	18.5	17.8	17.0	16.3	15.5
60	25.4	23.1	21.1	20.1	19.1	18.0	17.3
60	27.2	24.6	22.6	21.3	20.3	19.1	18.3
70	30.7	27.7	25.4	23.6	22.6	21.1	20.1
80	34.0	30.5	27.9	25.9	24.6	22.9	21.6
80	36.1	32.3	29.7	27.4	26.2	24.1	22.6
90	39.9	35.6	32.5	30.0	28.2	26.2	24.4
100	43.4	38.6	35.1	32.3	30.2	27.9	25.9
100	45.7	40.6	36.8	34.0	32.0	29.5	27.2
110	49.8	43.9	39.9	36.6	34.3	31.5	29.0
120	53.6	47.2	42.7	39.1	36.3	33.3	30.7
	Site Index 24.4 m						
20	6.9	6.9	6.9	6.9	6.9	6.9	6.9
20	9.4	8.9	8.4	8.1	7.9	7.9	7.6
30	14.2	13.5	12.4	11.9	11.7	11.4	10.9
40	18.0	17.0	15.7	15.0	14.5	14.0	13.5
40	19.6	18.5	17.3	16.3	15.7	15.2	14.7
50	23.6	22.1	20.6	19.3	18.5	17.8	17.0
60	27.4	25.4	23.4	21.8	20.8	20.1	19.1
60	29.2	27.2	24.9	23.4	22.1	21.3	20.3
70	33.3	30.7	27.9	26.2	24.6	23.6	22.4
80	37.1	34.0	30.7	28.7	26.9	25.7	24.4
80	39.4	36.1	32.5	30.5	28.7	27.2	25.7
90	43.7	39.9	35.8	33.3	31.2	29.5	27.7
100	47.8	43.4	38.9	36.1	33.8	31.8	29.7
100	50.3	45.7	40.9	38.1	35.6	33.5	31.2
110	54.9	49.5	44.5	41.1	38.4	36.1	33.5
120	59.4	53.3	47.8	43.9	40.9	38.4	35.6

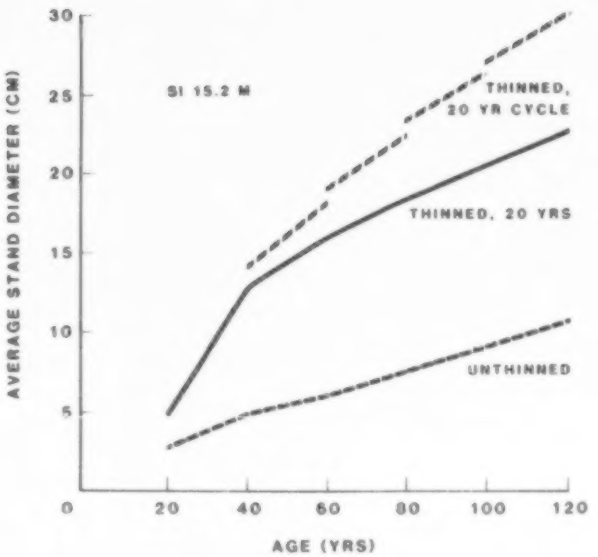

Figure 3. – Northern model estimates of average stand diameter – under no thinning, single thinning at 20 years to GSI 13.8, and thinning at 20-year intervals to GSI 13.8 – for stands initially stocked at 19,768 trees/ha and a site index of 18.3 m in Idaho and Montana.

at 80 years and 20.1 cm (7.9 inches) to 58.4 cm (23.0 inches) at 120 years for the range of GSI's and site indexes tested. On lands of typical site index (18.3 m, 60 ft) thinned on a 20-year cycle, trees reach 25.4 cm (10 inches) at 57 to 112 years of age for the GSI range of 9.2 to 27.5 m^2/ha (40 to 120 ft^2/acre). Above a GSI of 27.5, average diameter does not reach 25.4 cm within a 120-year rotation (fig. 4).

Similar effects of repeated thinning on average stand diameter were provided by the central model. Tables 11 and 12 summarize results from the central model, relative to stand age, stand density, and site index for a 20-year cutting cycle. Trees reach average stand diameters of 17.0 cm (6.7 inches) to 37.1 cm (14.6 inches) at 80 years and 22.6 cm (8.9 inches) to 59.4 cm (23.4 inches) at 120 years for the range of GSI's and site indexes tested. On site index 18.3 m (60 ft) lands with a 20-year cutting cycle, average stand diameters reach 25.4 cm (10 inches) at 62 to 114 years of age for the range of GSI's tested (fig. 5). Comparison of figure 5 with the curves in figure 4 shows the central model predicting larger average diameters at high stand densities than the northern model. This trend holds for all site indexes examined.

Height Growth

Height growth of lodgepole pine is known to increase with site index and decrease with increasing stand age and stand density. Effects on height growth of age and stand density (as represented by crown competition factor) are reflected in the density-corrected site index curves for lodgepole pine developed by Alexander and others (1967). These site index curves can be used to determine expected height of dominant trees, at different stand ages, for a wide range of stand density. Alternative methods of estimating the height of lodgepole pine have been developed by Stage (1975) and by Dahms (1975, 1983). These approaches can be used in place of site index equations to determine height of stands at future ages; or they can be used in conjunction with the site index approach.

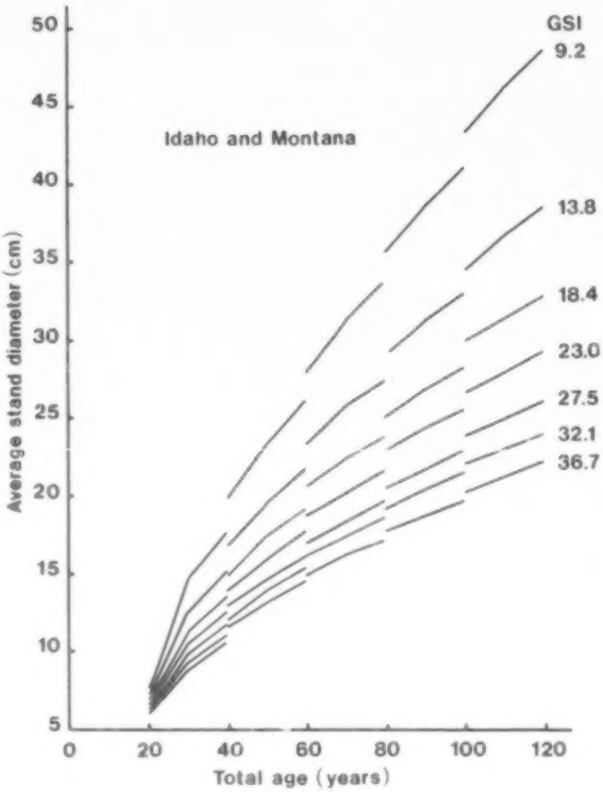

Figure 4. – Northern model estimates of average stand diameter in relation to age and growing stock index after thinning on a 20-year cycle, on site index 18.3 m lands in Idaho and Montana.

Average dominant height growth in the northern model follows site index curves with adjustments for stand density (Alexander and others, 1967) and equations for height growth of young trees in the Stand Prognosis Model (Wykoff and others, 1982). Height development in the central model also follows the same site index curves, but with adjustments downward to account for average codominant, as well as dominant height (Myers and others, 1967).

After precommercial thinning has secured height growth potential of stands, repeated thinnings have relatively minor effects on height growth. Still, both frequency and intensity of low thinnings are positively correlated with arithmetic increase in the mean height of the residual stand. Differences due to intensity of thinning are shown for a 20-year cutting cycle in figure 6 for mean height of dominant trees of the northern model and in figure 7 for mean height of dominant and codominant trees of the central model.

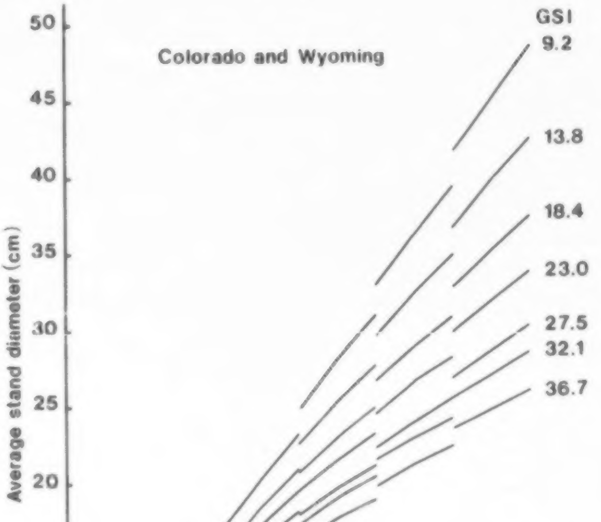

Figure 5. – Central model estimates of average stand diameter in relation to age and growing stock index after thinning on a 20-year cycle, on site index 18.3 m lands in Colorado and southern Wyoming.

Basal Area Increment

Stand basal area after culmination of mean annual increment is not closely related to stand volume (tables 1-4). However, stand basal area increment, like diameter growth, is strongly affected by site quality and thinning (figs. 8-9). Another factor influencing basal area development of stands is periodic mortality. Mortality relationships in the northern model are based on Lee's (1971) model for predicting average stand mortality rates. Adjustments are included as the stand approaches maximum basal area for a site class (Cole and Jensen, 1982). Mortality relationships in the central model for stands not infested with dwarf mistletoe depend on basal area and average stand diameter (Myers and others, 1971). No mortality is assumed to occur in managed stands with average diameter greater than 25.4 cm (10 inches) unless stand density, as measured by basal area, is high.

Comparison of basal area development at the extremes of thinning intensity shows that the northern model reduces basal

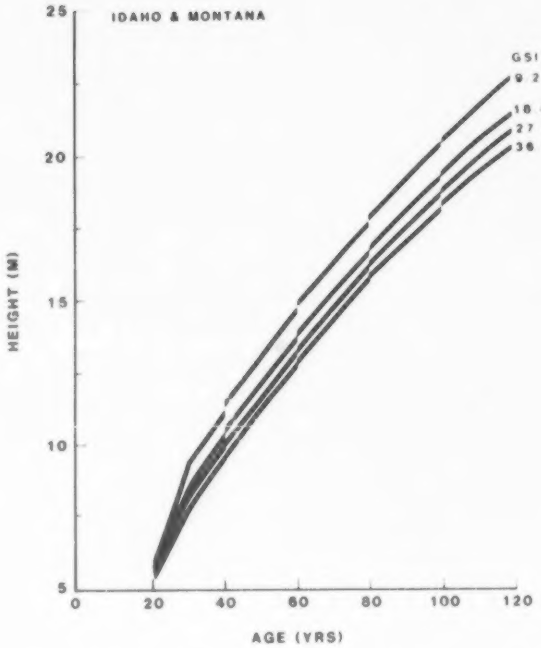

Figure 6. – Northern model estimates of average dominant height in relation to age and growing stock index after thinning on a 20-year cycle, on site index 18.3 m lands in Idaho and Montana.

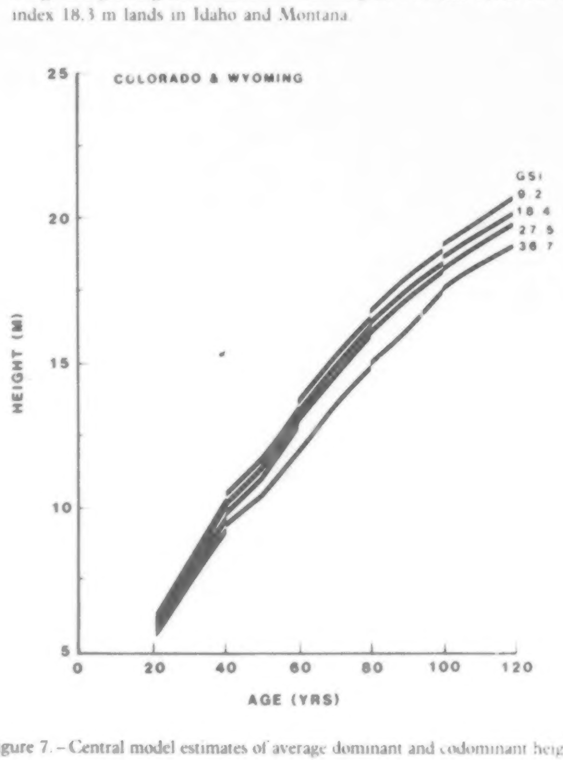

Figure 7. – Central model estimates of average dominant and codominant height in relation to age and growing stock index after thinning on a 20-year cycle, on site index 18.3 m lands in Colorado and southern Wyoming.

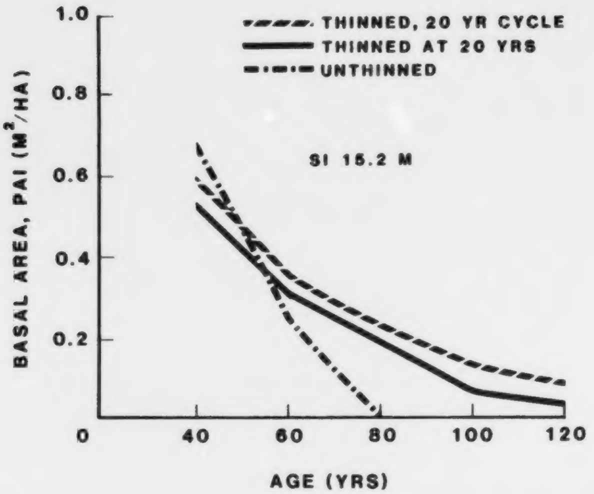

Figure 8. – Trend of periodic annual basal area increment, on site index 15.2 m lands, of unthinned, precommercially thinned, and repeatedly thinned stands initially stocked with 9,884 trees/ha in Idaho and Montana; according to northern model estimates.

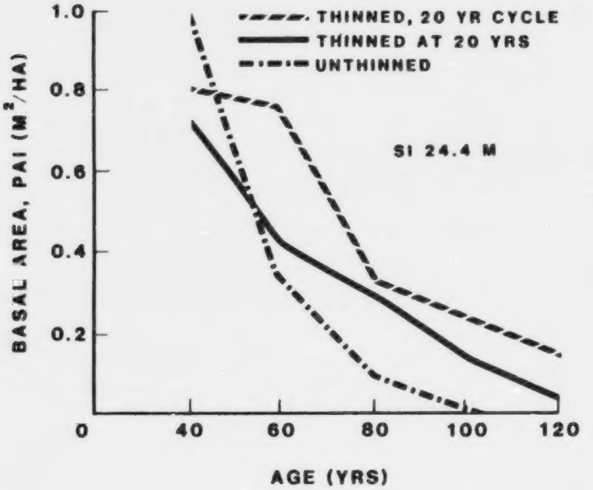

Figure 9. – Trend of periodic annual basal area increment, on site index 24.4 m lands of unthinned, precommercially thinned, and repeatedly thinned stands initially stocked with 9,884 trees/ha in Idaho and Montana; according to northern model estimates.

area growth more at high stand ages than does the central model (figs. 10 and 11). In the northern model, this reduction in growth is dependent on both slower average diameter growth and higher mortality rates. The central model assumes this mortality would be reduced to negligible amounts by frequent thinnings. The distinction between unmanaged and managed stands is not always easy to make when various degrees of management intensity are involved (McQuillan and Zuuring, 1983). In addition, since mortality is often a clustered event, both

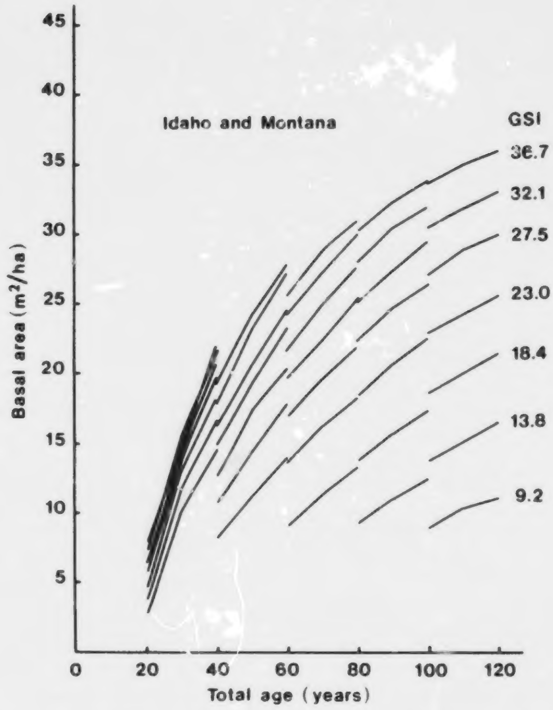

Figure 10. – Northern model estimates of basal area per hectare in relation to age and growing stock index, after thinning on a 20-year cycle, on site index 18.3 m lands in Idaho and Montana.

spatially and in time, samples from a relatively small number of plots may not be adequate to accurately assess long-term mortality rates. Prediction of mortality is, therefore, one of the weakest components in most forest growth models, especially when the distinction between various levels of management intensity is not adequately quantified.

Total Cubic Volume Growth

Mean annual increment (MAI) is a more objective criterion than standing volume for evaluating volume growth consequences of different intensities of management (Assman, 1970). Total volume MAI is related to age, site quality, stand density, and intensity and frequency of thinning.

In both unmanaged and precommercially thinned stands, effects of site quality on total volume MAI are much stronger than initial stand density, according to the northern model (fig. 12). Total volume MAI was increased slightly by precommercial thinning to GSI 13.8 of stand densities of 19,768 trees/ha (8,000 trees/acre) at a site index of 15.2 m (50 ft), but not at higher site indexes. Total volume MAI's of lower initial stand densities tested were not improved by a single precommercial thinning to GSI 13.8, regardless of site index. Effects of age, site, and stand density on cubic volume MAI are summarized in tables 1-4 for unmanaged stands and in tables 5-8 for a single precommercial thinning at age 20 years of the same site and stand density conditions.

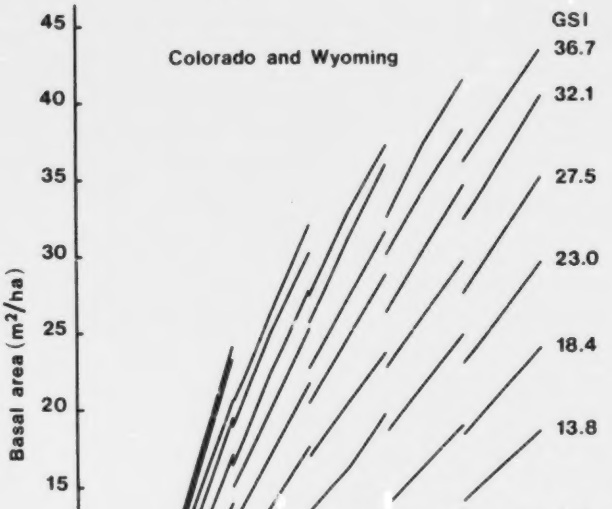

Figure 11. – Central model estimates of basal area per hectare in relation to age and growing stock index, after thinning on a 20-year cycle, on site index 18.3 m lands in Colorado and southern Wyoming.

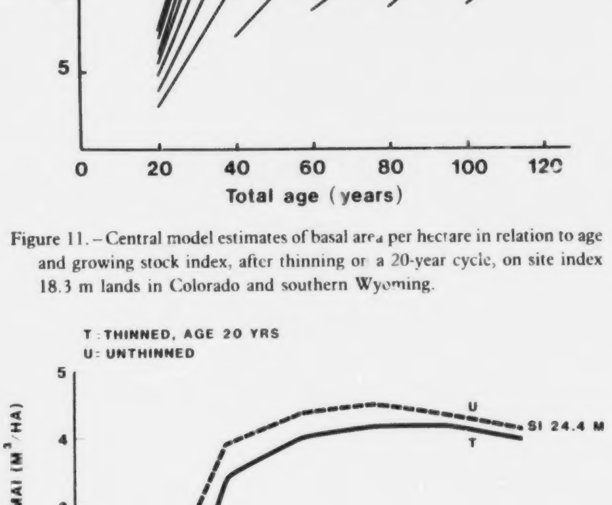

Figure 12. – Northern model estimates of effects of thinning and site quality on total volume mean annual increment (MAI) in stands initially stocked with 19,768 trees/ha in Idaho and Montana.

Intensity and frequency of repeated thinnings under intensive management also affect total cubic volume MAI in both models, as shown in figures 13 and 14 for an 80-year rotation and in figures 15 and 16 for a 120-year rotation. Mean annual total cubic volume increment of both models increases as GSI increases to at least 32.1 m^2/ha (140 ft^2/acre) and site index increases, but the rate of increase diminishes at GSI's beyond this level. For each GSI, total cubic volume MAI is greater at each higher site index; however, the differences become somewhat less with increasing site index in the northern model, whereas differences become greater in the central model. Mean annual increments are greater for the 80-year rotation than the 120-year rotation for the northern model. Mean annual increments are about the same for both rotations in the central model, except at lower site indexes and at GSI's of 27.5 m^2/ha (120 ft^2/acre) and above, where mean annual increments are larger for the 120-year rotation. The differences between the two models in the relationship of mean annual increment of total volume and rotation age are probably associated with differences in how they treat mortality and diameter growth at older ages, as discussed earlier for basal area increment.

Merchantable Cubic Volume Growth

Mean annual increment of merchantable cubic stand volume also is related to stand density, site quality, age, and thinning frequency – as well as to the minimum d.b.h. and top diameter for inclusion as merchantable volume. These effects are summarized for unmanaged stands (tables 1-4) and precommercially-thinned stands (tables 5-8) using the northern model.

On site index 24.4 m (80 ft) lands, unmanaged stands exceeding 9,884 trees/ha (4,000 trees/acre) at 20 years of age, produce no merchantable volume before the stand reaches 80 years of age (fig. 17). At a site index of 15.2 m (50 ft), the age to production of initial merchantable volume is 110 years. Even at these ages, only about half the stand volume is merchantable. A single precommercial thinning of these stands at age 20 years, however, lowers the age of production of merchantable volume to 40 years and raises the ratio of merchantable to total volume to about 90 percent at culmination of merchantable MAI. Culmination occurs at 100 to 110 years. Thus, precommercial thinning is seen to markedly increase the merchantable cubic volume yield of overstocked stands and to provide some merchantable volume after 40 years of age for subsequent thinnings under more intensive management.

Effects of intensity and frequency of thinning on merchantable volume in relation to site quality and age were determined with both the northern and central models (tables 13-14). For both models, merchantable cubic volume at rotation increases as site index increases and the GSI of the residual stand increases to at least 32.1 m^2/ha (140 ft^2/acre) (figs. 18-19). The differences in merchantable volume predicted by the northern model at given GSI's become somewhat less with increasing

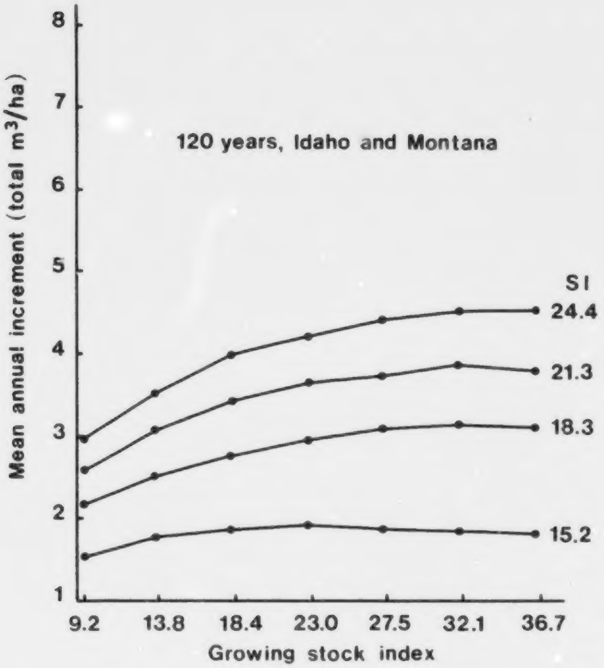

Figure 13. – Northern model estimates of mean annual total volume increment per hectare in relation to site index and growing stock index after thinning on a 20-year cycle, for an 80-year rotation in Idaho and Montana.

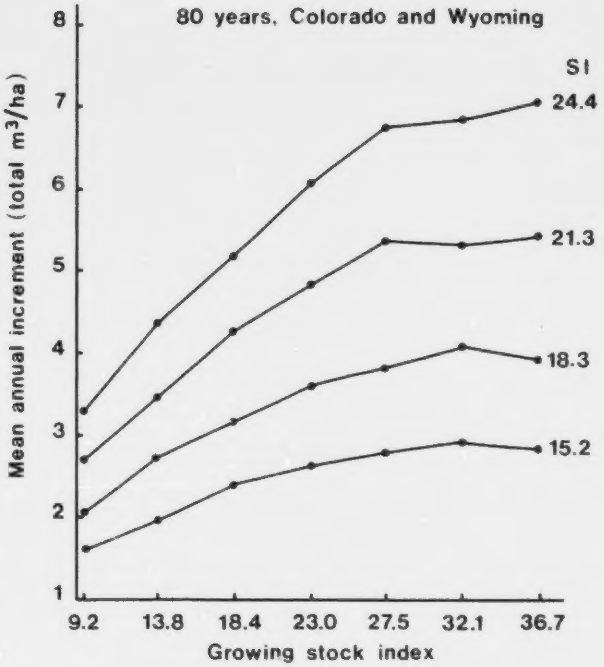

Figure 14. – Central model estimates of mean annual total volume increment per hectare in relation to site index and growing stock index after thinning on a 20-year cycle, for an 80-year rotation in Colorado and southern Wyoming.

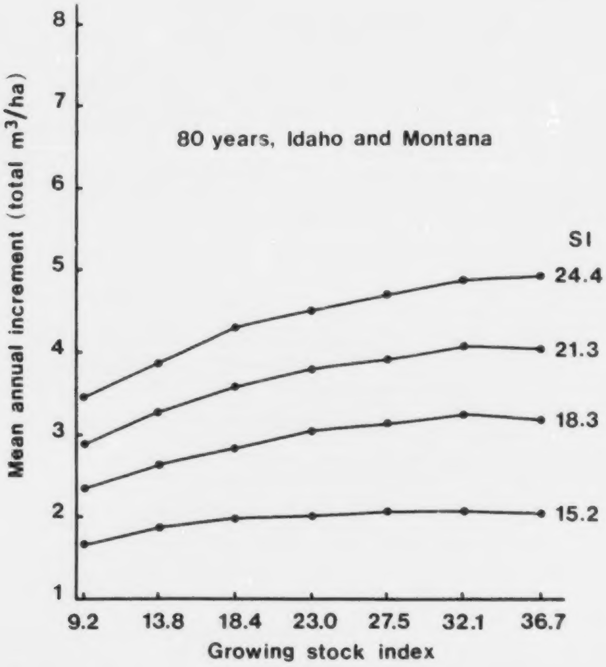

Figure 15. – Northern model estimates of mean annual total volume increment per hectare in relation to site index and growing stock index after thinning on a 20-year cycle, for a 120-year rotation in Idaho and Montana.

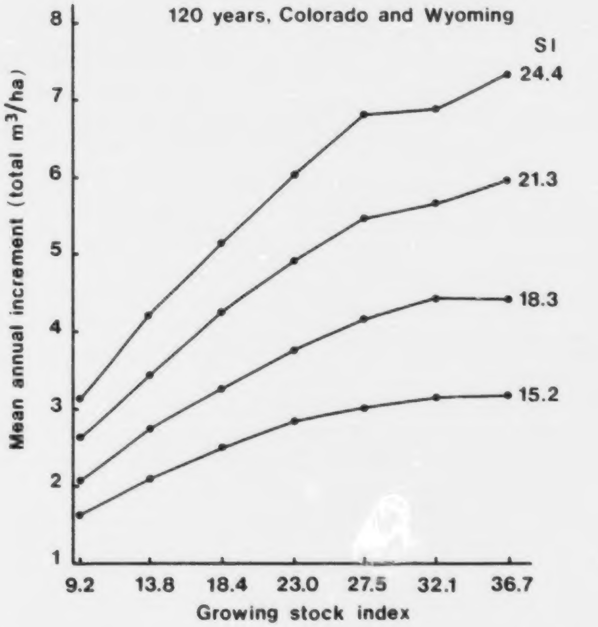

Figure 16. – Central model estimates of mean annual total volume increment per hectare in relation to site index and growing stock index after thinning on a 20-year cycle, for a 120-year rotation in Colorado and southern Wyoming.

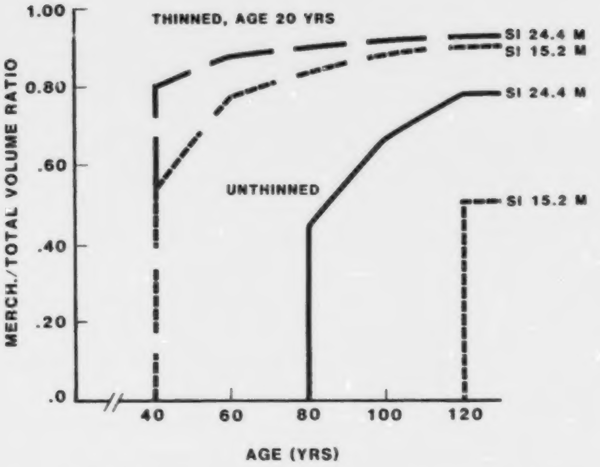

Figure 17.—Northern model estimates of effects of thinning and site quality on relationship of merchantable/total volume ratios to age of stands initially stocked at 9,884 trees/ha in Idaho and Montana.

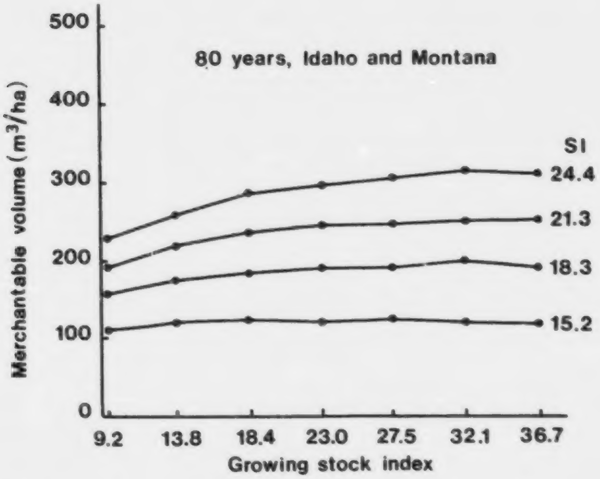

Figure 18.—Northern model estimates of merchantable volume production per hectare in relation to site index and growing stock index after thinning on a 20-year cycle, for an 80-year rotation in Idaho and Montana.

site index, whereas they become greater in the central model. Merchantable volume production is substantially lower at lower GSI's on moderate to high site indexes (tables 11-12). As GSI is reduced from 36.7 to 9.2 m^2/ha (160 to 40 ft^2/acre), merchantable volume production is reduced by about 25 percent for the northern model (fig. 18) and 50 percent for the central model (fig. 19).

For both models, merchantable cubic volume MAI also increases as GSI increases to at least 32.1 m^2/ha (140 ft^2/acre) and as site index increases (figs. 20-21). But differences due to site for a given GSI become somewhat less with increasing site index in the northern model, whereas they become greater in the central model. Merchantable cubic volume MAI is nearly the same for 80-year and 120-year rotations in the northern model, although the 120-year rotation is slightly higher at

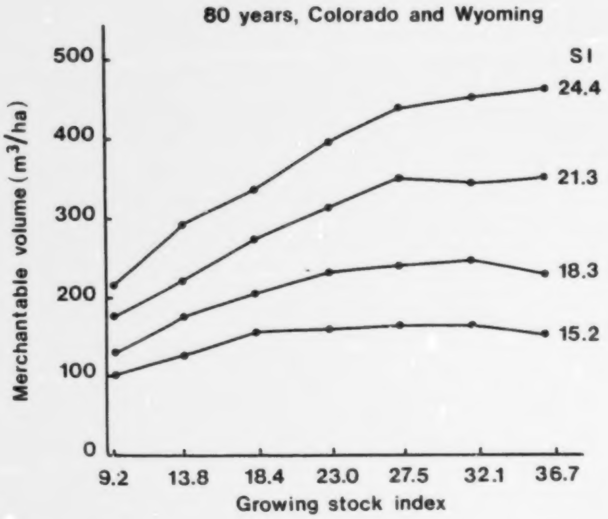

Figure 19.—Central model estimates of merchantable volume production per hectare in relation to site index and growing stock index after thinning on a 20-year cycle, for an 80-year rotation in Colorado and southern Wyoming.

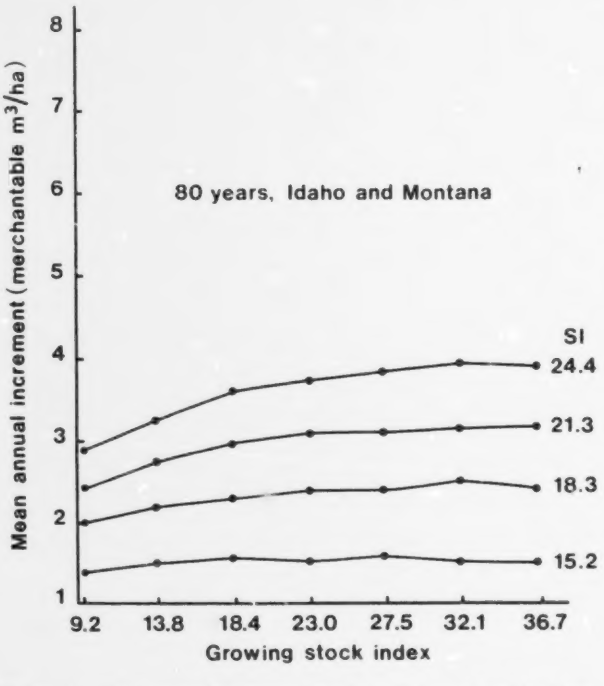

Figure 20.—Northern model estimates of mean annual merchantable volume increment per hectare in relation to site index and growing stock index after thinning on a 20-year cycle, for an 80-year rotation in Idaho and Montana.

intermediate site indexes (figs. 20, 22). In the central model, merchantable volume MAI is consistently greater for the 120-year rotation, for all site indexes (figs. 21, 23). Generally, repeated thinnings with the central model, on a 20-year cycle, produce more merchantable volume over the same time span with two 120-year rotations than with three 80-year rotations. Less frequent cutting cycles, on the order of 40+ years, would change this tendency in favor of shorter rotations.

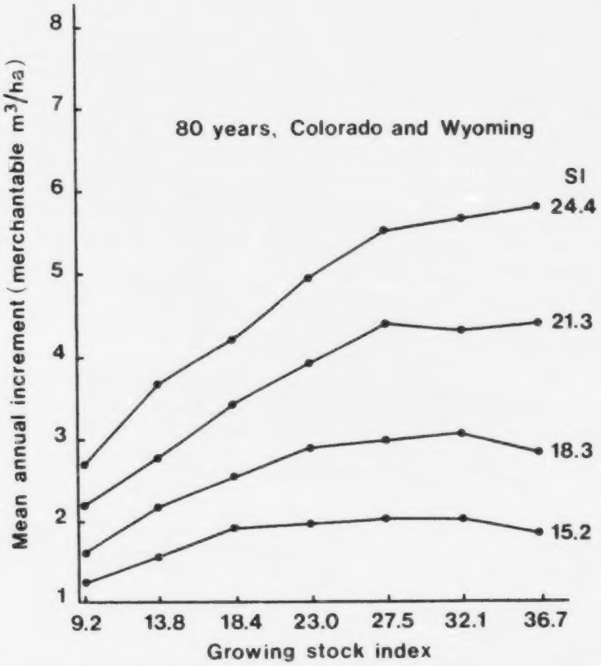

Figure 21. – Central model estimates of mean annual merchantable volume increment per hectare in relation to site index and growing stock index after thinning on a 20-year cycle, for an 80-year rotation in Colorado and southern Wyoming.

Whether merchantable volume production potential can be achieved depends on the amount of money which can be invested in periodic thinning. Based on 2.5 m^3 (90 ft^3) per cord and assuming that a minimum commercial yield amounts to 12.6 m^3/ha (2 cords/acre), the number of precommercial thinnings required before commercial yields can be attained are shown in tables 15 and 16 for the range of growing stock indexes, site indexes, cutting cycles, and rotation ages tested. If the minimum commercial/yield is 6.3 m^3/ha (1 cord/acre), generally one less precommercial thinning is required. If only one precommercial thinning is possible, managers can increase flexibility by thinning to low GSI's initially, and allowing density to increase gradually over the rotation. Another alternative is to delay reentry into stands assuming adverse impacts of pests will not be experienced.

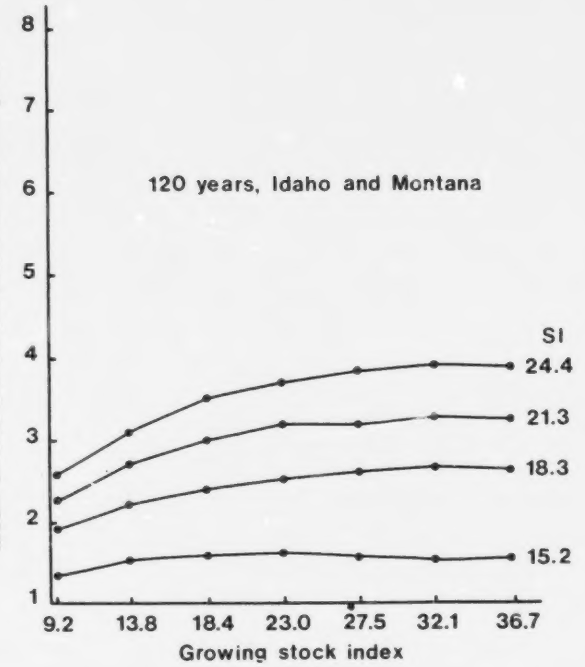

Figure 22. – Northern model estimates of mean annual merchantable volume increment per hectare in relation to site index and growing stock index after thinning on a 20-year cycle, for a 120-year rotation in Idaho and Montana.

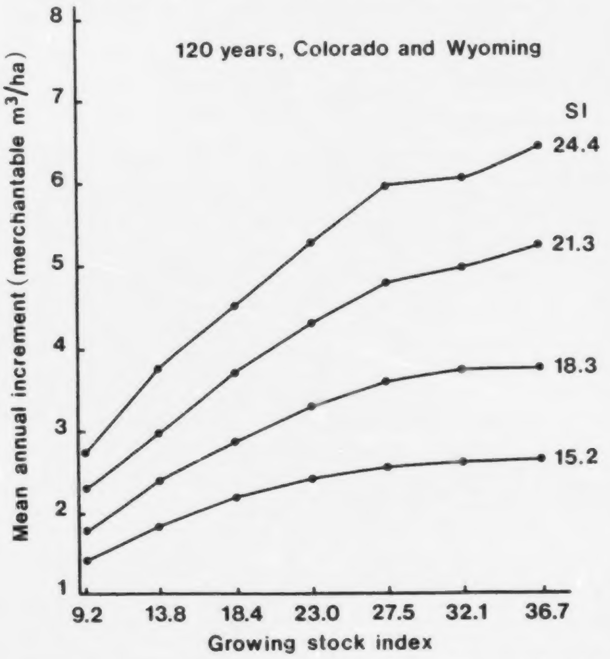

Figure 23. – Central model estimates of mean annual merchantable volume increment per hectare in relation to site index and growing stock index after thinning on a 20-year cycle, for a 120-year rotation in Colorado and southern Wyoming.

Table 13.—Northern model estimates of merchantable volume production per hectare (trees 11.7 cm d.b.h. and larger to a 10.2-cm top) in relation to rotation age, cutting cycle, growing stock index, and site index in Idaho and Montana

Rotation Age	Cutting Cycle	Growing stock index						
		9.2	13.8	18.4	23.0	27.5	32.1	36.7
- - - years - - -		cubic meters						
					Site Index 15.2 m			
80	10	99.1	111.6	119.4	120.1	127.5	124.5	118.0
120	10	139.6	168.5	182.9	185.2	185.5	186.8	186.1
80	20	110.4	120.8	123.7	121.8	124.4	120.4	119.1
120	20	158.9	183.5	189.2	192.8	188.9	185.0	185.4
80	30	117.0	124.6	125.0	124.5	119.8	118.6	117.4
120	30	172.5	192.2	196.3	198.0	186.4	184.2	185.0
					Site Index 18.3 m			
80	10	141.9	162.2	177.4	191.0	191.5	201.2	200.2
120	10	195.4	236.1	271.4	288.3	309.8	309.1	321.6
80	20	158.2	175.2	183.0	190.7	190.5	198.8	190.8
120	20	227.3	264.5	286.3	301.2	310.8	318.6	314.4
80	30	166.8	183.3	196.8	191.9	203.8	195.8	197.3
120	30	245.3	279.2	304.4	309.6	325.9	318.7	320.2
					Site Index 21.3 m			
80	10	175.7	203.2	224.1	235.2	250.6	252.9	258.8
120	10	229.1	289.1	327.0	353.4	369.1	384.1	387.0
80	20	191.9	219.0	235.8	245.8	246.7	250.2	252.2
120	20	267.8	322.9	357.6	380.3	380.1	391.0	388.4
80	30	207.6	234.1	245.3	262.0	250.0	259.4	260.5
120	30	296.8	344.4	377.8	397.5	396.6	403.7	397.5
					Site Index 24.4 m			
80	10	203.7	236.6	266.4	282.1	292.1	314.5	305.0
120	10	234.8	322.6	375.2	415.5	433.7	451.5	446.3
80	20	227.8	258.5	286.3	296.9	305.2	314.3	310.6
120	20	304.0	368.9	419.0	441.1	458.6	467.5	464.1
80	30	242.0	272.0	297.7	310.5	319.3	317.7	316.9
120	30	331.1	398.0	443.8	467.5	482.2	484.6	485.4

Table 14.—Central model estimates of merchantable volume production per hectare (trees 15.2 cm d.b.h. and larger to a 10.2-cm top) in relation to rotation age, cutting cycle, growing stock index, and site index in Colorado and southern Wyoming

Rotation Age	Cutting Cycle	Growing stock index						
		9.2	13.8	18.4	23.0	27.5	32.1	36.7
--- years ---		cubic meters						
					Site Index 15.2 m			
80	10	94.1	118.4	145.3	154.5	167.3	170.5	160.4
120	10	151.1	199.6	246.3	272.6	299.6	328.3	324.2
80	20	99.1	124.0	152.6	157.1	161.2	161.4	148.3
120	20	164.4	216.4	258.5	283.9	301.3	308.7	311.8
80	30	103.8	133.3	143.0	159.9	172.1	163.8	149.9
120	30	175.2	228.8	253.7	294.3	323.7	321.2	302.4
					Site Index 18.3 m			
80	10	122.1	161.3	192.4	221.6	245.0	248.9	251.8
120	10	192.0	258.8	315.1	370.3	413.8	441.2	454.6
80	20	126.2	173.3	202.3	230.2	237.7	244.4	226.0
120	20	206.7	281.6	337.8	389.9	427.0	444.4	444.6
80	30	147.5	184.1	208.6	230.5	244.8	242.7	245.3
120	30	233.5	300.2	355.6	400.3	445.5	450.1	458.6
					Site Index 21.3 m			
80	10	153.1	211.4	253.9	298.0	328.1	350.8	351.6
120	10	235.9	327.5	401.7	474.1	534.1	585.2	592.2
80	20	172.7	219.7	273.1	311.8	350.2	344.2	350.3
120	20	267.4	351.8	438.0	509.8	570.1	591.3	625.3
80	30	193.4	248.3	297.2	328.3	346.0	338.2	342.8
120	30	295.0	392.2	473.9	534.3	574.6	604.6	609.5
					Site Index 24.4 m			
80	10	184.9	253.6	320.3	364.7	416.5	456.3	467.5
120	10	267.5	387.1	493.0	573.4	658.0	726.9	732.2
80	20	210.8	291.7	336.0	395.1	441.6	452.5	464.2
120	20	319.4	444.8	535.1	627.4	711.7	722.1	768.4
80	30	239.2	327.3	378.1	438.8	479.5	467.5	447.5
120	30	356.6	491.8	590.1	686.9	749.4	770.0	756.6

Table 15.—Number of precommercial thinnings in relation to rotation length, site index, and frequency and intensity of thinning in Idaho and Montana, as simulated by the northern model

Rotation Age	Cutting Cycle	Growing stock index (GSI)						
		9.2	13.8	18.4	23.0	27.5	32.1	36.7
- - - years - - -		cubic meters						
		Site Index 15.2 m						
80	10	6	6	6	6	6	6	6
120		10	10	10	10	10	10	10
80	20	1	2	3	3	3	3	3
120		1	2	4	5	5	5	5
80	30	1	1	2	2	2	2	2
120		1	1	2	4	4	4	4
		Site Index 18.3 m						
80	10	3	5	6	6	6	6	6
120		3	5	6	8	9	10	10
80	20	1	1	2	2	3	3	3
120		1	1	2	2	3	5	5
80	30	1	1	1	1	1	2	2
120		1	1	1	1	1	2	4
		Site Index 21.3 m						
80	10	1	3	4	5	6	6	6
120		1	3	4	5	6	10	10
80	20	1	1	1	1	2	3	3
120		1	1	1	1	2	3	5
80	30	1	1	1	1	1	1	2
120		1	1	1	1	1	1	2
		Site Index 24.4 m						
80	10	1	2	3	4	6	6	6
120		1	2	3	4	6	8	10
80	20	1	1	1	1	2	2	2
120		1	1	1	1	2	2	2
80	30	1	1	1	1	1	1	1
120		1	1	1	1	1	1	1

Table 16.—Number of precommercial thinnings in relation to rotation length, site index, and frequency and intensity of thinning in Colorado and southern Wyoming, as simulated by the central model

Rotation Age	Cutting Cycle	Growing stock index (GSI)						
		9.2	13.8	18.4	23.0	27.5	32.1	36.7
- - - years - - -		cubic meters						
					Site Index 15.2 m			
80	10	5	6	6	6	6	6	6
120		6	6	7	7	9	8	10
80	20	2	3	3	3	3	3	3
120		2	3	3	3	3	4	4
80	30	2	2	2	2	2	2	2
120		2	2	2	2	2	2	3
					Site Index 18.3 m			
80	10	5	5	5	5	5	6	6
120		5	5	5	5	5	6	7
80	20	2	2	2	2	2	3	3
120		2	2	2	2	2	3	3
80	30	1	1	2	2	2	2	2
120		1	1	2	2	2	2	2
					Site Index 21.3 m			
80	10	4	3	4	4	4	4	5
120		4	3	4	4	4	4	5
80	20	2	2	2	2	2	2	2
120		2	2	2	2	2	2	2
80	30	1	1	1	1	2	2	2
120		1	1	1	1	2	2	2
					Site Index 24.4 m			
80	10	3	3	3	3	4	3	4
120		3	3	3	3	4	3	4
80	20	1	1	2	2	2	2	2
120		1	1	2	2	2	2	2
80	30	1	1	1	1	1	1	2
120		1	1	1	1	1	1	2

INTEGRATION OF TIMBER PRODUCTION WITH OTHER RESOURCES

Understory vegetation in lodgepole pine forests is potentially important as forage for big game and livestock, but to increase forage, the manager must reduce timber production by thinning to relatively low GSI's (Basile, 1975). Thinning second-growth stands not only increases amount of forage, but also results in changes of composition of understory species (Dealy, 1975). To increase understory production to moderate levels, stocking must be reduced to GSI 13.8 m^2/ha (60 ft^2/acre) or less. In addition, maintenance of forage production requires frequent stand entries.

Lodgepole pine forests are important for water yield in the Rocky Mountains due to cold climates with short growing seasons and the accumulation of overwinter snowpacks (Hoover, 1975). Simulation of water yield over a 120-year rotation, with a 30-year cutting cycle on site index 18.3 m (60 ft) lands, showed that estimated water yield was influenced little by GSI's ranging from 18.4 to 27.5 m^2/ha (80 to 120 ft^2/acre) (Leaf and Alexander, 1975). No comparisons were made at lower stand densities, but more water should be available for streamflow. An important unknown factor is water use by increased understory vegetation at low GSI's.

APPLICATION OF MODELS TO OTHER REGIONS

Comparison of the estimated yields from the two models discussed in this paper indicate that the northern model more closely agrees with estimated yields from natural stands in central Oregon (Dahms, 1975, 1983) for the range of site indexes tested. As expected, the central model generally overestimated volume production of these stands because it was developed on managed-stand data from more subalpine environments.

A recent study comparing results of 10-year growth projections of the central model with performance of dwarf mistletoe-infested and noninfested stands in British Columbia was completed by Laut (1984). Volume growth of infested stands was found to be underestimated by the central model. This was apparently the result of general underestimation of diameter growth and overestimation of mortality. Noninfested plots and infested plots had similar errors. As noted by Laut, earlier comparisons of model performance indicated that the impact of dwarf mistletoe was overestimated. Nevertheless, differences with actual stand performance may be due to underestimation of diameter growth and overestimation of mortality rather than overestimation of disease effects.

Results such as these rudimentary comparisons point to the need for revising variable density functions for height and diameter growth and mortality when applying existing models to new locations and stand conditions. Smith (1983) discusses methods for revising regional coefficients of growth models to improve model performance in a subregion or extended area. Such refinements can be made on the models reported here, when new data become available. In the interim, the models compared here appear to represent reasonably well the growth and yield characteristics of managed and unmanaged lodgepole pine stands in the regions in which they were developed.

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LODGEPOLE PINE BIOMASS MODELS

Roger C. Chapman

ABSTRACT

Although considerable attention has been devoted to estimating the cubic and board foot volume of lodgepole pine, much less attention has been devoted to developing models for predicting biomass of entire stems or of stem components.

Results of a biomass study completed in northeastern Washington are reported. The study was focused on the development of biomass models for small diameter conifers. One hundred and two lodgepole pine stems were destructively sampled during the study. Linear regression techniques were used to develop biomass models.

Weighted regression models are presented for predicting oven-dry bole biomass, total above-ground biomass, and the vertical distribution of bole biomass for stems greater than 15.2 cm in diameter at breast height. Weight basal area models and their behavior are discussed.

INTRODUCTION

Although considerable attention has been devoted to estimating the cubic and board foot volume of lodgepole pine *Pinus contorta* Doug., much less attention has been devoted to developing models for predicting biomass yields of individual lodgepole pine stems or stands. The magnitude of the lodgepole pine resource, the need to assess the yields associated with stocking reductions or commercial thinnings, and interest in wood fired electrical generation have led to increased interest in estimating lodgepole pine biomass. Some of the models structures that have been used to predict lodgepole pine biomass and the results of a biomass study in northeastern Washington State are summarized in the subsequent paragraphs.

LODGEPOLE PINE BIOMASS MODELS

Linear regression procedures have traditionally been used to develop individual stem and component biomass models. The model structures and predictor variables chosen reflect the characteristics of the components to be estimated, the desire to use easily measured or estimated characteristics and modelers' mathematical and statistical expertise. The allometric relationship between the commonly measured tree characteristics, the biomass components and the heteroscedasticity associated with biomass data has led many modelers to use the logarithmic model

$$\ln(W) = b_0 + b_1 \ln(x) \qquad (1)$$

where W is the component biomass,
ln is the natural logarithm, and
x is some easily measured tree characteristic, often diameter at breast height (D) or height (H), a power of D or H, or a combined variable such as D^2H.

Some modelers who have used the logarithmic model have used $(s^2/2)$ to correct for bias associated with the logarithmic model; others have not. Simple polynomial type models, linear models often with combined variables such as D^2H, and weighted linear models have also been used to derive estimates of lodgepole pine biomass.

Moir and Francis's (1972) conclusions with respect to needle fascicle biomass "that pine stands in different environments and with different tree spacings must be interpreted individually insofar as components of variation of ... biomass are concerned" explains at least partly why there is such a wide variety of crown component models.

One of the earliest lodgepole pine biomass models was developed by Storey, *et al.* (1955) who used diameter at the base of live crown dc in the model

$$Wc \cdot Hc = b_0\,dc \qquad (2)$$

where Wc is crown weight, and
Hc is the crown length to predict crown weight.

Kiiki (1967) estimated crown weight and weight of live branches with the model

$$\log(W) = b_0 = b_1\log(D) + b_2\log(CW) \qquad (3)$$

where log is the logarithm to the base 10,
D is diameter at breast height (dbh), and
CW is crown width.

Branch and foliage weight of lodgepole pine in British Columbia was modeled by Kimmens (1974) using the models

$$\log(W) = b_0 + b_1\log(D^2H) \qquad (4)$$

and

$$\log(W) = b_0 + b_1\log(D \cdot CL) \qquad (5)$$

where CL is crown length.

Johnstone (1970, 1971) used the model

$$\log(W) = b_0 + b_1\log(D^2H) \qquad (6)$$

to estimate the biomass yields of boles, stumps, stem bark, needles, roots, total tree, and total aboveground biomass in a 100-year-old lodgepole stand in Alberta.

The crown weights of lodgepole pine in the Rocky Mountains in the United States were described by Brown (1976) using the models

$$\ln(W) = b_0 + b_1\ln(D) \tag{7}$$

and

$$\ln(W) = b_0 + b_1D^3 + b_2D^2R \tag{8}$$

where R is the crown ratio • 10.

The proportion of foliage (P) in the live crown was predicted with the model

$$P = b + bD.$$

The polynomial and combined variable models

$$W = b_0 + b_1D + b_2D^2 + b_3D^3 \tag{9}$$

$$W = b_0 + b_1D + b_2H + b_3D^2H + b_4D^2 + b_5D^3 \tag{10}$$

$$W = b_0 + b_1D^2H \tag{11}$$

were used by Singh (1982a, 1982b) to estimate stump, stem, live branch, and total aboveground bole biomass of lodgepole pine in the prairie provinces of Canada.

Gary (1976) developed 10 linear models for predicting the weight of crown components of 80 year lodgepole pine in Wyoming. Predictor variables studied included diameter at breast height, diameter at the base of live crown, crown length, tree height, and combinations of these variables. Needle, branch wood, and needle plus branch wood weights of individual branches were modeled using weights of branch components or branch basal diameter. Gary (1978) characterized the vertical distribution of crown biomass in these 80-year-old stands using the Weibull distribution.

Moeur (1981) is notable for developing models for predicting foliage biomass of inland northwest species using stand and individual tree characteristics. For diameters greater than or equal to 8.9 cm, foliage biomass was estimated with the model

$$\begin{aligned}\ln(W) = b_{0i} + b_1\ln D + b_2\ln(H) + b_3\ln(CL) +\\ b_4\ln(A) + b_5\ln(TPA) + b_6\ln(DREL)\end{aligned} \tag{12}$$

where b_{0i}, the intercept, is species specific,

A is age,

TPA is trees per acre, and

DREL is relative diameter (tree dbh/quadratic mean stand diameter).

For diameters less than 8.9 cm on the model

$$\ln(W) = b_{0i} + b_{1i}\ln(CL) + b_2\ln(A) + b_3\ln(TPA) \tag{13}$$

was developed to estimate foliage biomass.

Because the Growth Prognosis Model (Stage, 1973, Wykoff *et al.*, 1982) does not require age as an input variable, alternative models were developed for predicting foliage biomass. For trees greater than or equal to 8.9 cm, Moeur developed the alternative model

$$\begin{aligned}\ln(W) = b_{0i} + (b_1 + 2b_4)\ln(D) - b_4\ln[\Delta D^2] +\\ b_2\ln(H) + b_3\ln(CL) + b_5\ln(TPA)\\ + b_6\ln(DREL)\end{aligned} \tag{14}$$

where ΔD^2 is periodic squared diameter increment.

For stem less than 8.9 cm the alternative model was

$$\ln(W) = b_{0i} + b_1\ln(H) + b_2\ln(CL) + b_3\ln(TPA) \tag{15}$$

Weight to volume models (conversion factors) are commonly used in forestry. The increased interest in estimating weight has led to the construction of weight-basal area models and tables and the development of models for predicting weight from volume.

Singh (1982) developed the model

$$W = b_0V^{b_1} \tag{16}$$

where W is the total weight above ground biomass, and

V is the green merchantable volume in m^3 above a 0.3 m stump to a top diameter of 7.6 cm

to predict total aboveground biomass for lodgepole pine in the prairie provinces of Canada.

INLAND NORTHWEST BIOMASS STUDY

In 1978 the U.S. Department of Energy funded a study to develop estimates of biomass yields of small diameter conifers. In the study, 35 conifer stands in northeastern Washington State were sampled. The study was focused on developing individual stem biomass equations for trees growing in conifer stands whose average diameter at breast height was less than 30.5 cms (12 inches). Although many of the stands sampled were pure lodgepole pine, a significant number contained ponderosa pine, *Pinus ponderosa*, Laws., western larch, *Larix occidentalis*, Nutt., or Douglas-fir, *Pseudotsuga menziesii*, (Mirb.), Franco plus several other species common to the region. Biomass models for the other species considered are shown in Chapman, *et al.* (1984).

In each stand selected for sampling, four to six points were systematically selected for measurement. At each point a 14.49 square meter (1/300th acre) circular plot wwas established in which stems less than 12.7 cms (5 in) were measured. Stems greater than 12.7 cms were selected for measurement using variable radius plot techniques.

At each point one to two trees were randomly selected for destructively sampling. The bole was cut into 1.22 m (4 ft) sections except the butt section which was cut into two 0.61 m (2 ft) sections to facilitate handling. Each bole section was weighed green and a 2.5 cm to 7.6 cm disk was cut and weighed. The disks were subsequently oven dried at 103°C and the ratios (disk oven-dried weight/disk green weight) were used to estimate the oven-dry weight of the sections. All the branches and needles were oven dried.

In the 102 lodgepole pine stems destructively sampled, the bole (wood + bark) accounted for 90.3 percent of the aboveground biomass. The branches (wood + bark) accounted for 6.4 percent and the foliage accounted for 3.3 percent of the aboveground biomass. The dimensional characteristics of the destructively sampled trees are shown below in table 1.

Table 1.–Dimensional characteristics of 102 destructively sampled lodgepole pine stems.

Characteristic	Size
Av. dbh (cm)	15.5
Av. top height (m)	17.07
Av. cu. vol. (cu. m)	00.20
Av. oven-dry bole weight (kg)	105.32
Av. oven-dry crown weight (kg)	39.82
Av. crown width (m)	3.81

MODEL DEVELOPMENT

The GLM (general linear model), RSQUARE (all possible regression), NONLIN (non-linear regression), and PLOT procedures of the statistical Analysis System (SAS) were used to develop linear models for predicting oven-dry weights of lodgepole pine biomass components. Prior work by Chapman (1979) indicated that weighted model

$$W = b_0 + b_1(D^2H) \tag{17}$$

with the weight of $1/D^2H$ could be used to estimate bole biomass of small diameter conifers.

This model was fitted to the bole (wood + bark) data. Inspection of the residuals led to a modification of the model and a decision to build a model for diameters less than 15.2 cm (6 in) and a model for diameters greater than 15.2 cm. The 15.2 cm break point was suggested by the pattern of residuals and is somewhat arbitrary.

The model

$$W = b_0 + b_1(D^2H^{1.5}) \tag{18}$$

where W is component oven-dry weight in kg,

D is diameter at breast height in cms,

H is total height in m

with a weight of $1/D^2H^{1.5}$ was subsequently fitted to each of the diameter groups. The coefficients and associated statistics for the bole (wood + bark) and total aboveground biomass are shown in table 2.

DISTRIBUTION OF BOLE BIOMASS

Estimation of bole biomass to a specified top diameter d is useful in determining the weight yields associated with thinnings and in estimating residual fuel loadings following a harvesting operation or stocking reduction. The weighted model

$$r_w = b_0 + b_1(D^2H) + \sum_{i=1}^{3}[b_i \sin(i\pi r_d)] + \sum_{i=1}^{3}[c_i \cos(i\pi r_d)] \tag{19}$$

where d is inside bark diameter in cm,

D is dbh in cm,

H is total height in meters,

r_w is the ratio of attained oven-dry weight (w_d) at top diameter d to total bole weight w_T, (w_d/w_T),

π is pi, 3.1416...,

r_d is (d/D), the ratio of attained inside bark top diameter to diameter at breast height outside bark,

was developed to predict the proportion of total bole oven-dry weight attained to a desired inside bark top diameter, d above dbh, for stems greater than or equal to 15.2 cm. The weight used in the model was 1/[d/D(1-d/D)].

Table 2.–Model coefficients and statistics associated with the prediction of lodgepole pine oven-dry bole weight (wood + bark) and total aboveground biomass[1].

Description	b_0	b_1	R^2	RMSE
Bole (wood + bark)				
Dbh < 15.2 cm	00.6706	.0043	97	441
Dbh ≥ 15.2 cm	22.4032	.0029	86	441
Total aboveground biomass				
Dbh < 15.2 cm	00.8512	.0046	97	287
Dbh ≥ 15.2 cm	17.5612	.0034	86	512

[1] $W = b_0 + b_1D^2H^{1.5}$, where W is weight in kg, D is dbh in cm, and H is total height in m.

The form of this model was suggested by the sigmoid shape of the curve and the desire to have a flexible model structure that could be used to describe the distribution of bole biomass of all the species studied. The D^2H term, although not significant, was retained to provide a size parameter in the model. The estimated coefficients and associated statistics for the model are shown below in table 3.

The cumulative proportion of total bole weight to specified (d/D) ratio is shown in figure 1. Because the combined variable D^2H has relatively little influence, the curve shown in figure 1 is applicable for any combination of diameters and heights that would normally be found.

Oven-dry weights to any specified top diameter d can be estimated using the preceding model and the bole weight model. The errors of estimation associated with the prediction of oven-dry weight to a specified top are somewhat difficult to calculate because the estimate is a product of two random variables with common predictor variables.

Table 3. – Model coefficients and statistics associated with modeling the proportion of attained total bole oven-dry weight at specified inside top diameter d.

Variable	Coefficient
intercept	1.1225
D^2H	0.71057×10^{-7}
$\sin(\pi r_d)$	−.6266
$\cos(\pi r_d)$	.4473
$\sin(2\pi r_d)$	−.1134
$\cos(2\pi r_d)$	.5841
$\sin(3\pi r_d)$	.1837
$\cos(3\pi r_d)$	.0149
Statistics	
R^2	.99
RMSE	.21

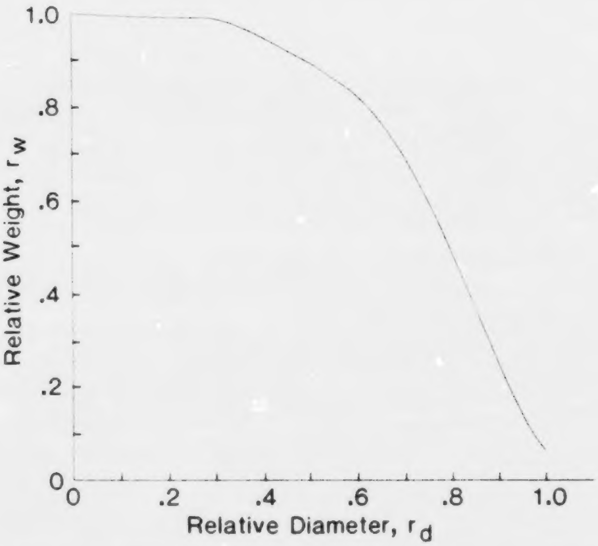

Figure 1. – Proportion of attained total oven-dry bole weight as a function of relative diameter (top diameter i.b./d.b.h.(o.b.)).

WEIGHT-BASAL AREA RELATIONSHIPS

To facilitate cruise calculations in lodgepole pine stands, weight-basal area (WBAR) models were developed. The bole oven-dry models shown in table 2 were divided by basal area to obtain the WBAR model

$$\text{WBAR} = 8538.34\ (1/D) + 54.79\ H^{1.5} \qquad (20)$$

where WBAR is weight, kg/m^2 for diameters less than 15.2 cm, and

$$\text{WBAR} = 285245.13\ (1/D) + 36.71\ H^{1.5} \qquad (21)$$

for diameters greater than or equal to 15.2 cm.

The WBAR models have many of the same attributes as volume-basal area (VBAR) models. The influence of diameter on WBAR is much less than the influence of height. However, as diameter decreases its influence on WBAR increases. These characteristics are clearly evident in figure 2. From figure 2 it is also apparent that accurate estimates of height are needed to obtain accurate estimates of weight.

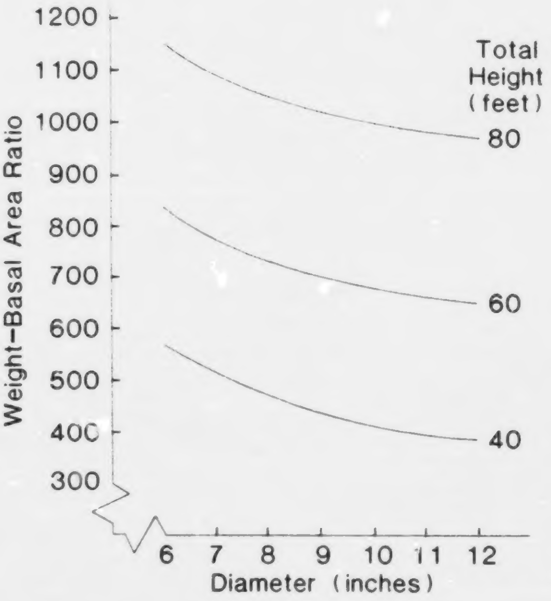

Figure 2. – Weight-basal area ratios for lodgepole pine for selected diameters and total heights.

BOLE WEIGHT-CUBIC VOLUME RELATIONSHIPS

Although the preceding bole weight models can be easily included in an inventory processing program, the models are not particularly useful when attempting to estimate biomass yields from a previously prepared cubic volume stock table. The model

$$W = .3796 + 0.1176D + 440.8302V \qquad (22)$$

where V is the total inside bark in cubic meters, was developed to provide a simple method of estimating weight from cubic volume stock tables.

CONCLUSIONS

Biomass estimation excluding weight-volume conversions has traditionally been the fief of academicians. Biomass will undoubtedly remain an important measure of tree and stand productivity in research studies. Field foresters and managers are gradually recognizing the utility of models for predicting biomass yields of lodgepole stands.

Much more work is needed in lodgepole pine biomass estimation to facilitate its availability to operations foresters. The models reviewed and the study described are essentially cross sectional and yield only glimpses of the dynamics of lodgepole biomass production. Biomass simulators are needed that foresters can easily use to estimate the biomass yields associated with a variety of treatment regimes. Although it may not be economically feasible to build a large flexible biomass simulator, existing single tree distance independent stand simulators such as the Growth Prognosis Model can be modified to provide biomass estimates as well as the traditional volume statistics.

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MANAGING LODGEPOLE PINE ECOSYSTEMS FOR GAME AND RANGE VALUES

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ABSTRACT

Variety and production of forage species understory to lodgepole pine forest are usually low and the nutritional value of the dominant forages (mushrooms excepted) tends to be moderate at best. Consequently, wild and domestic ungulate use of these stands as summer range is correspondingly low. Associated nonforested communities, such as dry and wet meadows, generally give lodgepole pine ecosystems their primary forage values in the absence of management. When tree canopies are opened by logging, wildfire, or insect epidemics, however, forage production, nutritional values, and diversity may increase substantially. This effect can last up to 20 years or more before canopy closure again reduces the forage resources for game and livestock. Major benefits occur in the first 10 years; longer if thinning or other managerial action is taken. Where soil depth, fertility, or moisture preclude commercial timber production, particularly on stagnated stands, management for wildlife habitat and livestock grazing may be the best use. Where practical, cheap means to this end (e.g., liberal rail, post, or fuelwood cutting) could supplement scarce habitat or range development funds. Patterned clearing:cover patches should be planned to ensure that increased forage is used since wild ungulates tend to avoid the centers of large openings. Seeding clearcuts to adapted grasses and forbs can greatly increase forage production and seasonal range values.

INTRODUCTION

The use of plant communities characterized by lodgepole pine as big game habitats and livestock ranges was usefully reviewed by Dealy (1975) and Basile (1975). Their summaries of pertinent literature were generally current to 1973 and, therefore, my analysis will focus upon research reported since then. A considerable literature on various ecological aspects affecting lodgepole pine ecosystems has been generated in the intervening decade; especially on: (1) climax association classification, (2) fire history, and (3) successional patterns with fire, insect attacks, and clearcutting, to list just a few. All of these factors interface directly or indirectly with habitat values for wild and domestic ungulates, but an exhaustive review would constitute a symposium in itself.

My intent is, then, to narrow discussion to certain aspects related to the major ungulates – mule deer, elk, cattle and domestic sheep – that occupy lodgepole pine types as summer range. It is obvious that the complex interspersion of cover types over space (different sites) and time (seral communities on the same site) make it extremely difficult to generalize animal-lodgepole pine relations; generalizations at least that are definitive from the Canadian to Colorado Rockies and the volcanic highlands of central Oregon to those of Yellowstone National Park. Consequently, the reader is cautioned not to extrapolate specific research too broadly without testing hypotheses at local or regional levels.

Lodgepole pine forests, both climax and seral, are extensive at mid-elevations in the central Rockies of Utah, Idaho, Wyoming, and Colorado. They tend to have rather poor understories in regards production and diversity of species. Many are dominated by one or a few low shrubs, most notably of the genus *Vaccinium,* with low relative amounts of forbs and graminoids. Because of their large area, they form important summer ranges for deer, elk, and moose; but it is due to the associated non-forested plant communities that the ecosystems are valuable to wild and domestic ungulates.

DEER AND ELK

My graduate students and I established a study in the mid-1970's to examine the foraging behavior, habitat selection, and dietary nutrition aspects of mule deer and elk use of a lodgepole pine ecosystem in the Uinta Mountains of northeastern Utah. Our purpose was to determine the relative contribution to animal welfare of 5 major habitat subunits – dry and wet meadows, created forest openings (clearcuts), mature and stagnated forest. These observably differed in area, understory composition and production, and animal selection. By using tractable animals we could obtain more specific information than is possible with remote methods such as pellet-group counts, feeding-site analyses, or radio telemetry. We recognized this approach had limitations as well, particularly in regards differences in flight behavior between tame animals and their wild counterparts in the event of human disturbance, but it was the best suited to our objectives. The data generated were voluminous on a biweekly basis from mid-June to mid-September, with emphasis upon plant species, not just forage classes (Collins *et al.,* 1978, Deschamp *et al.,* 1979, Collins and Urness 1983, Pallesen 1979).

Deer and elk forage use in the five habitat subunits was investigated by allowing animals to graze in morning and evening bouts in pure types. Diet composition was estimated via intensive bite counts and dry-weight consumption was estimated from simulated bites (clipped, dried, and weighed) of each species.

Nutritional analyses of individual forage species and deer and elk diets throughout summer provided a good assessment of nutritional status. Chemical determination for calcium, phosphorus, fiber and crude protein (N x 6.25), plus in vitro dry matter digestibilities (IVDMD), yielded the most complete data of dietary quality anywhere in the lodgepole pine type.

Habitat selection of deer and elk and activity budgets of elk were determined by releasing animals on 24-hour sessions every two weeks whereby free choice was afforded them of the various subunits for specific activities. Percentage of the entire day spent on each activity was calculated from scan-sampling (Altmann 1974), a procedure that simply records location and activity of each animal under observation every 10 minutes around the clock.

Diet Composition

Summer diets of mule deer appear in Figure 1, summarized by habitat subunit and forage class. Relative availabilities indicated the forb class was strongly selected for in all subunits, as were mushrooms in the forested subunits. Grasses and sedges in the non-forested subunits and browse in forested subunits were taken in amounts less than their relative availabilities. Stuth and Winward (1977) also found forbs dominated deer diets on meadows in the central Oregon lodgepole pine type (Pumice Region) until early August when forb maturity caused a shift toward bitterbrush use in the forest. Regelin *et al.*, (1974) and Wallmo *et al.*, (1972) reported the dominance of browse in summer deer diets in a lodgepole pine type in central Colorado which was similar to our study area except it lacked meadow subunits. I have no ready explanation why this difference occurred; perhaps the fact that their animals were maintained on alfalfa hay and a nutritionally balanced concentrate fed ad libitum, while our animals were maintained on natural forages in the study area, was responsible. Thus, the greater use of browse of only moderate quality in Colorado was possible because nutrient demand was met by the artificial foods of high quality, whereas our deer needed to maximize nutrients in their grazing of forested subunits and they expended more effort searching for scattered forbs. The lean condition of our animals tended to support this speculation.

Summer diets of elk in the Uinta Mountains differed most strongly between forested and non-forested plant communities. Forbs as a class dominated diet selection on meadows and clearcuts, while browse and mushrooms dominated diets from forested habitats; indeed, elk foraged in stagnated forest only when mushrooms were available in late summer (Figure 2). Elk more effectively utilized the lodgepole ecosystem generally than deer because grasses and sedges formed the bulk of production on meadows (the most productive subunits) and elk consumed large amounts, but deer did not. Condition of elk at the end of summer was better than deer, even though all were nonproducing yearlings, except that one deer was a two-year-old.

Nutritional Relationships

The contributions of the 5 habitat subunits to nutritional wellbeing of deer and elk differ in much the same way as habitat use since these animals tend to spend most of their foraging time in subunits that yield the most per unit of effort expended. If one looks just at diet quality within each subunit, the uniformity is striking. That is, from a qualitative standpoint, diets from all subunits are quite good (Tables 1 and 2), especially during early and late periods. But when one examines the relative potential contributions of the subunits to animal nutrition, then a very different picture emerges (Table 3). Several points can be made from these data on nutrient concentrations:

1. the lodgepole pine type as represented by the Uinta Mountains is better summer range for elk than deer (e.g., a greater amount of total forage production is used by elk)
2. the wet meadow subunit is clearly best for elk as foraging areas, but deer exhibit no such tie to any subunit since most of the mature forest forage resource is a nonpreferred browse (*Vaccinium scoparium*) of only moderate value
3. the importance of *clearcut* areas (approximately 4% of total) is much greater than the *stagnated forest* (nearly 70% of total).

Consequently, there is a tremendous potential for increasing big game habitat values by creating more openings; so long as an adequate balance of cover and foraging areas is maintained.

A unique aspect of deer and elk nutrition in the Uinta Mountains was the importance of fungi to mid- and late-summer diets. Mixed mushrooms as a group usually were among the top three contributors to IVDMD and CP in dry meadows, and most often the top contributor in mature and stagnated forest (Table 4). Since mushrooms developed after frequent rain showers and were most abundant on forested subunits, there is slight potential for managerial enhancement except maintenance of adequate mature and stagnated forest areas distributed throughout ungulated home ranges. An idea of the great attractiveness of mushrooms to elk is conveyed by them being the only foraging item that was ever observed to be taken (or attempted) from one animal by another.

Habitat Selection and Development

Deer were more closely associated with forested subunits for all activity categories than elk (Table 5). One must view this with caution since wild elk are likely more constrained in their use of open habitats than tame elk. Nevertheless, our data did demonstrate the importance of dry and wet meadows to elk, and the need for careful management where optimization of their habitat is wanted. Pedersen *et al.*, (1980) found a similarly strong preference for riparian habitats in the Blue Mountains of northeastern Oregon, as did Marcum (1976) in western Montana and Hayden-Wing (1979) in Idaho. Timber management practices affected elk use of habitats both negatively and positively in western Montana lodgepole pine forests (Lyon and Basile 1980), and Marcum (1979) found elk use of openings

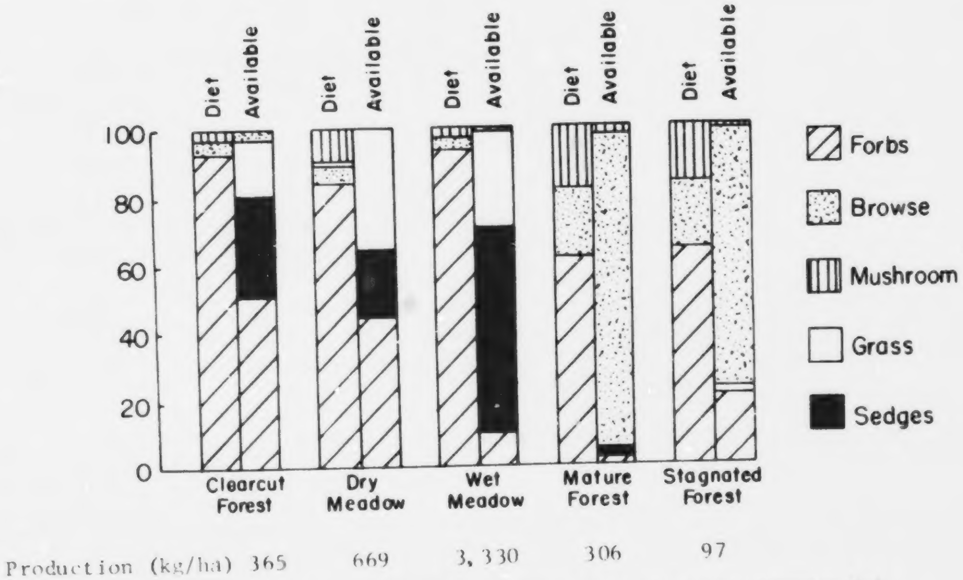

Figure 1. – Forage availability (% of dry weight) and summer diets of mule deer in the Unita Mountains, Utah, by forage class and habitat subunit (from Deschamp *et al.*, 1979).

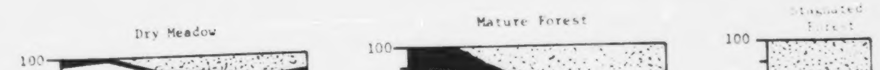

Figure 2. – Summer diets of elk in the Unita Mountains, Utah, by forage class and habitat subunit (from Collins *et al.*, 1978).

Table 1.—Crude protein percentages in weighted diets (composited diets) during summer in lodgepole pine habitats in the Uinta Mts., Utah (from Pallesen 1979).

Period	Dry meadow	Wet meadow	Clearcut	Mature forest	Stagnated forest
			MULE DEER		
Jun 16	15.6 (16.3)		10.2(12.1)	16.6(17.4)	
Jun 30					13.7(12.7)
Jul 14		14.2(13.9)		10.8(10.9)	
Jul 25	13.0(13.2)		8.9(9.7)		
Aug 8				12.4(12.6)	9.4(9.4)
Aug 30		18.2(18.2)	14.9(15.1)		
Sep 13	14.9(14.9)			13.0(13.9)	14.6(14.5)
Mean	14.5	16.2	11.3	13.2	12.6
			ELK		
Jun 16	18.7(18.8)		16.7(16.9)	13.2(14.5)	
Jun 30		15.9(16.9)			
Jul 14	14.2(13.9)		10.8(10.4)		
Jul 25		13.3(14.9)		13.1(13.2)	16.6(17.4)
Aug 8			14.4(14.3)		
Aug 30	14.5(14.2)	12.4(12.1)		14.6(14.6)	16.2(14.8)
Sep 13					
Mean	15.8	13.9	14.0	13.6	16.4

Table 2.—In vitro digestibility percentages of weighted diets (composited diets) during summer in lodgepole pine habitats in the Uinta Mts., Utah (from Pallesen 1979).

Period	Dry meadow	Wet meadow	Clearcut	Mature forest	Stagnated forest
			MULE DEER		
Jun 16	63.5(65.9)		70.1(63.9)	49.3(52.8)	
Jun 30					60.3(50.9)
Jul 14		64.2(64.8)		68.2(68.7)	
Jul 25	77.9(81.1)		48.9(48.7)		
Aug 8				74.2(85.4)	77.4(76.7)
Aug 30		65.8(65.4)	59.4(62.0)		
Sep 13	83.1(87.7)			77.3(90.5)	71.7(62.7)
Mean	74.8	65.0	59.5	67.3	69.8
			ELK		
Jun 16	71.4(72.0)		73.9(72.6)	39.6(41.6)	
Jun 30		66.9(69.4)			
Jul 14	78.9(83.3)		81.5(79.8)		
Jul 25		58.8(61.5)		59.2(60.9)	69.1(68.9)
Aug 8			64.6(65.7)		
Aug 30	81.6(80.7)	73.0(67.9)		64.4(78.6)	62.4(59.6)
Sep 13					
Mean	77.3	66.2	73.3	54.4	65.8

Table 3.—Nutrient concentration (kg/ha) in subunits of lodgepole pine habitat in the Uinta Mts., Utah (from Pallesen 1979).

		Dry meadow	Wet meadow	Clearcut	Mature forest	Stagnated forest
Percent area		12	3	4	12	69
Total production		669	3330	365	306	97
Potential forage	MD[1]	108	96	94	148	15
	E	231	965	141	144	15
In vitro dry matter digest.	MD	88	62	46	126	12
	E	186	655	93	144	2
Crude protein	MD	15	17	9	19	2
	E	33	116	20	21	2
Neutral deterg. fiber	MD	37	33	53	43	5
	E	157	540	49	61	8
Calcium	MD	0.7	0.8	0.6	1.3	0.1
	E	1.2	14.0	0.5	1.1	0.2
Phosphorus	MD	0.4	0.4	0.4	0.5	0.0
	E	0.6	2.2	0.5	0.6	0.1

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[1] MD = deer; E = elk, based on 50% utilization of forage species consumed by each animal species.

Table 4.—Importance of mushrooms (% of dietary total) to mule deer and elk diets in mid to late summer in the Uinta Mts., Utah (from Pallesen 1979).

		Date									
		7/14		7/25		8/8		8/30		9/13	
Species	Subunit	IVDMD[1]	CP	IVDMD	CP	IVDMD	CP	IVDMD	CP	IVDMD	CP
Mule deer	Wet meadow	---[2]	---	---	---	---	---	4(6)	6(5)	---	---
	Dry meadow	---	---	---	---	13(4)[3]	23(2)	---	---	ND[4]	15(2)
	Clearcut	---	---	---	---	---	---	3(5)	3(5)	---	---
	Mature forest	---	---	---	---	28(2)	38(1)	---	---	26(2)	37(1)
	Stagnated forest	---	---	---	---	8(3)	14(3)	---	---	50(1)	50(1)
Elk	Wet meadow	---	---	8(6)	14(3)	---	---	---	---	---	---
	Dry meadow	9(4)	13(2)	---	---	---	---	9(3)	7(2)	---	---
	Clearcut	---	---	---	---	7(4)	16(4)	---	---	---	---
	Mature forest	---	---	72(1)	67(1)	---	---	50(1)	69(1)	---	---
	Stagnated forest	---	---	82(1)	85(1)	---	---	42(1)	42(1)	---	---

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[1] IVDMD = in vitro dry matter digestibility, CP = crude protein. [2] A dash indicates either no test, or no contribution of mushrooms on that date. [3] Numbers in parentheses are order of descending importance. [4] ND = no data, but it would likely have been second or third in importance.

including clearcuts was less than their availability except in xeric forest areas with poor understory.

Deer used wet meadows and clearcuts heavily for grazing but not for resting. Given the low relative amount of area in natural openings in the Uinta Mts., and the fact that deer grazed clearcuts more than any other subunit, it is obvious that timber management offers great opportunities for habitat improvement, especially in stagnated forest. Production of forbs and browse was initially good on clearcuts, particularly those where slash was burned, but reestablishment of lodgepole pine seedlings was rapid and dense. Habitat development can be active as well as passive. Unless tree thinning occurred, most forage benefits for ungulates were eliminated within 20 years. Edgerton (1983) also found forage production waning after 15 years in lodgepole pine/bitterbrush types in the Pumice Region of central Oregon. Thinning could extend the forage resource for a significantly longer time (Austin and Urness 1982) in forest succession. Maintenance of permanent openings in stagnated forest areas could perpetuate a greatly increased forage base.

Seeding adapted grasses such as orchardgrass (*Dactylis glomerata*), smooth brome (*Bromus inermis*), and timothy (*Phleum pratense*) and forbs such as sweetclover (*Melilotus* sp.) and alfalfa (*Medicago* sp.) can have strong effects on forage production and use (Roppe and Hein 1978, McLean and Clark 1980, Lyon 1973). Elk were observed using green growth of orchardgrass on revegetated roads and clearcuts shortly after snowmelt in the Uinta Mountains. Such preferred forages can pull animals off heavily impacted winter-spring ranges and should be more widely used in areas of forest disturbance.

Activity Budget

The average elk day throughout summer was nearly half (12 hours) spent grazing, 44% resting and ruminating, and 6% all other activities (Figure 3). Thus summer range in lodgepole pine ecosystems, as elsewhere, is a place for maximal nutrient processing and storage. For example, we found elk consuming forage at a far greater rate (g/kg $BW^{0.75}$) than is reported for range livestock and speculated that elk digestive physiology might reveal mechanisms that give them a greater innate ability to capitalize on high feed availability when quality is also high. The very frequent feeding bouts around the clock appear to support this view (Figure 4; Craighead *et al.*, 1973).

Recent studies of deer, reindeer, and moose also indicated that these ungulates exhibited elevated intake rates in summer as contrasted with livestock (Collins and Urness 1983, p. 658). Such behavior likely compensates for normally restricted forage quality and availability during winter dormancy by allowing for the rapid deposition of reserve energy (fat) and protein (muscle mass) in the late summer and fall, which is then catabolized in the lean winter months.

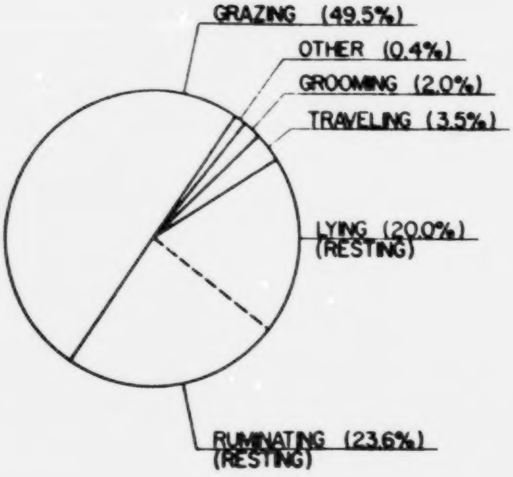

Figure 3. – Mean relative time expenditure for the 24-hour elk day based on observations of 7 animals for 6, 24-hour periods (from Collins *et al.*, 1978).

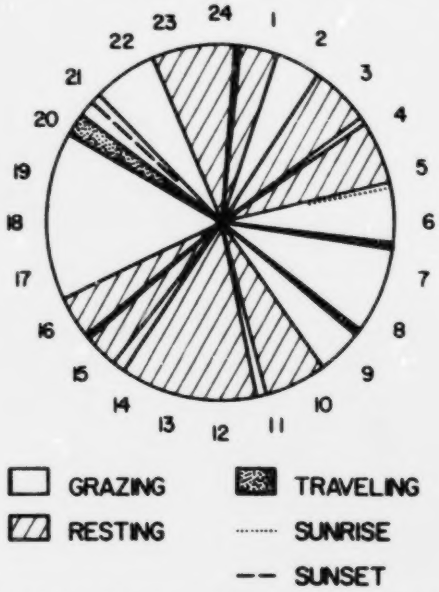

Figure 4. – A typical, 24-hour activity pattern of 7 elk on lodgepole pine summer range (from Collins *et al.*, 1978).

LIVESTOCK

Basile (1975) rightly viewed lodgepole pine ecosystems as quite limited in potential for supporting animal units of livestock in an unmanaged state due to low forage production or palatability of native species. Forage production is adequate only in non-forested communities and the overall resource is, consequently, less for livestock than elk because the latter species is more mobile and flexible in use of abundant browse of low palatability to livestock (e.g., *Vaccinium* sp.) in forested areas.

Table 5.—Habitat selection by mule deer and elk for various activity categories in a lodgepole pine ecosystem in the Uinta Mts., Utah (from Collins and Urness 1983).

Subunit	Percent total area used		Percent					
			All activities		Grazing		Resting	
	Deer	Elk	Deer	Elk	Deer	Elk	Deer	Elk
Wet meadows	3.0	2.7	14.8	46.8	30.6	43.6	0.0	50.5
Dry meadows	1.2	11.7	1.4	20.6	3.0	33.6	0.0	15.6
Clearcuts	4.9	4.4	24.8	8.4	36.3	14.6	4.1	0.7
Revegetated roads	0.6	0.6	0.0	1.9	0.5	3.0	0.0	0.0
Mature forest	13.3	11.9	10.0	12.4	13.0	3.3	8.1	20.7
Stagnated forest	77.0	68.7	48.9	9.8	16.6	1.9	87.8	12.7
Total non-forested	9.7	19.4	41.0	77.7	70.4	94.8	4.1	66.8
Total forested	90.3	80.6	58.9	21.2	29.6	5.2	95.9	33.4

Unless tree thinning on clearcuts is practiced, the effective foraging period for livestock is about 15 to 20 years, with the peak at about 11 years (800-1000 kg/ha). Thinning plus seeding of adapted non-native grasses could improve the situation, particularly in light of the accelerated interest in lodgepole pine as a commercial species in the Northwest and Canada. The proportion of lodgepole forest in clearcuts has greatly increased during the past decade.

Indeed, McLean and Clark (1980) have shown considerable grazing capacity for cattle on seeded clearcuts in lodgepole pine and spruce forests in British Columbia. Clipping studies indicated forage production was 2 to 4 times that on unseeded clearcuts (average yields of seeded species was 590 to 1540 kg/ha, with a maximum of 2,265 kg/ha). Yield was progressive for the first 5 years and the long-term practice of aerially seeding wildfire burns suggests increased forage likely lasts up to 20 years before canopy closure. Value of seeded species appeared best for early-season use due to their more rapid maturity contrasted to native species such as pinegrass (*Calamagrostis rubescens*). Some seeded species (e.g., orchardgrass) are more likely to produce fall growth. Damage to conifer tree seedlings was slight when grazing season and intensity were properly managed, extensive if forage use was excessive. Trampling, not browsing, was the cause of observed damage to young trees.

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MANAGING LODGEPOLE PINE ECOSYSTEMS AS WATERSHEDS

Robert H. Swanson

ABSTRACT

The lodgepole pine forest type occupies portions of the Colorado, Columbia, Fraser, Missouri and Saskatchewan river headwaters in Canada and the United States. The on-site needs of fish for habitat and clean water, as well as the needs of downstream water users must be considered during any forestry operations in these watersheds.

Clear-cutting of lodgepole pine forests alters streamflow by localizing snow accumulation and reducing evapotranspiration. The physical features of a managed forest that most affect its water-yielding characteristics are treed-cleared edge and clear-cut size. A 50:50 pattern of treed and clear-cut patches no larger than 2-6 tree heights across in any direction should produce maximum water yield from immature, stagnant, or mature lodgepole pine forests anywhere within its range.

The Northern Forest Research Centre has produced an interactive FORTRAN program for the hydrology portion of the USFS WRENSS procedure. This simple-to-use procedure estimates the annual water yield change that will occur under a wide variety of silvicultural practices.

INTRODUCTION

Watershed management is management for a specific water-oriented goal. It is not necessarily the same as good forest management, fisheries management or any other type of "multiple use" management. One would hope that the implementation of a watershed management system could be described as good forest management. However, one should not be surprised if management for a water-oriented goal results in different rotations and cutting patterns than management for any other forest product.

Lodgepole pine of commercial quality occurs from central California to the Yukon Territory. Annual precipitation over this region ranges from less than 300 mm in such widely separated places as Bend, Oregon, and Whitehorse, Yukon Territory, through a moderate 500 mm in Colorado to over 2000 mm in Oregon, Washington and southeastern Alaska. Throughout most of this range, snowfall is heavy (40 to 60% of annual precipitation), supplying the major portion of soil moisture for early season growth of lodgepole pine (Satterlund 1975; Lotan and Perry 1983). However, the species also thrives on the Eastern Slopes of the Canadian Rockies, where snowmelt from a light winter snowpack is augmented by moderate to heavy rain in May and June (Hillman *et al.*, 1978).

The wide areal distribution of lodgepole pine forests makes it difficult to generalize on the need for watershed management in these forests. Lodgepole pine occupies substantial portions of the headwaters of rivers such as the Athabasca, Colorado, Columbia, Fraser, Missouri and Saskatchewan. The latter five have large population centers downstream. The importance of watershed management in these headwaters varies directly in proportion to the needs of those water users.

There is no question of the value of water in the Colorado River. The water receives heavy domestic and agricultural use and is apportioned among a wide variety of users. The small headwaters catchments of the Columbia and Fraser rivers contain tributary streams vitally important to the Pacific Salmon fisheries. On the other hand, the waters of the Athabasca River are mainly used for local fishing and boat traffic. Watershed management would necessarily receive higher priority in the headwaters of the Colorado, Columbia and Fraser rivers than in those of the Athabasca.

The seasonal distribution of normal streamflow, and the time at which water is needed downstream are also of importance in establishing a need for watershed management in the headwaters. For example, many of the streams in Canada flow north and are normally ice filled downstream at the time of snowmelt in their more southern headwaters. If a combination of high natural flow and ice is already creating a problem for downstream users, a forest cutting scheme that would augment flow during the snowmelt period by a major amount would generally not be desirable. Most clear-cutting practices do augment flow during the snowmelt period (Swanson and Hillman 1977).

Watershed management is a form of forest management designed to produce desired streamflow characteristics. One objective of any watershed management program must be to enhance the usability of water for water users. Within such an objective, the following three broad categories of management may occur:

1. Management to protect the watershed and tree cover to retain the beneficial forest influences on soil and channel stability, water quality and flow timing. According to Hoover (1975), the "least risky" way to achieve this would be to leave the forest untouched.
2. Management to protect the stream and its inhabitants from undesirable changes in water quality or stream habitat. This type of management requires that the manager pay particular attention to erosion-sedimentation processes.
3. Management to deliberately increase usable water supply. This type of management must necessarily be a response to users' requests.

Once a water yield objective has been defined, then the response of forest management can take one of the following five forms:

a. The water users' requests are considered unimportant. They must live with the timber management plan.
b. Timber production is the prime goal; however, wherever possible, and if timber production costs are not unduly affected, then water users' needs will be considered and accommodated within the management plan.
c. Timber and water are equally important coproducts. The management plan will reflect concerns for both with neither occupying an overriding position to the detriment of the other.
d. Water is the primary product. Timber harvesting and measures to minimize fibre production costs will be accommodated as long as they do not unduly affect water production goals.
e. Water is the only management product. Timber harvesting, if done at all, must be done solely for the purpose of enhancing or maintaining prescribed water benefits.

In my opinion, most present-day forest management on watersheds falls under the first or second type of response. Except for "leaving the forest untouched," each of the above three categories of management represents some management activity on the part of the land manager to satisfy the needs of timber and water users. Such activity must be based on the energy exchange characteristics of sites and vegetation (Satterlund 1972) if it is to achieve predictable results.

There are two ultimate users of the product of watershed management: those on-site and those at some remote point downstream. There is a legitimate concern that increased water in the stream channel, seemingly desirable for downstream users, may be accompanied by increased sediment to the detriment of instream residents. Unfortunately, the concerns that people express for water values are often concerns about aesthetics or a desire to prevent logging in their particular playground. The watershed manager must carefully define who his customers are, if their problems relate to water, and if and/or how these concerns can be met by some form of forest manipulation.

In many instances, downstream water users have already provided the impetus for water management. Up to this point in time, the emphasis by water managers has been to increase supply by diversion and storage. This emphasis is being questioned, and one of the growing fields of research is that of water demand management, i.e. the manipulation of demand to coincide with the supply (Tate and Reynolds 1983). Further, the president of Resources for the Future (Castle 1983) has stated that in the 1980s, water conservation and efficiency of use will receive greater emphasis than interbasin water transfers. In my opinion, managing a forested watershed in a manner that will optimize its usable water yield is a valid way to conserve and improve water supply within a river basin.

Watershed management is not just management to increase water yield; it is also management to protect the land surface from erosion, the stream from degradation and the quality of the water. Most studies have shown that surface erosion and the sedimentation of streams can be effectively controlled through the application of proper engineering techniques, close supervision of activities during the road construction and skidding phases of timber extraction operations and prompt reclamation of disturbed sites (Hoover 1975; Anderson *et al.*, 1976). Other studies have shown that some sediment in streams originates from mass wasting and slumping into the stream channel. These occurrences represent a soil stability problem that is often associated with excessive on-site soil water. In areas where precipitation greatly exceeds evapotranspiration, the role of trees in removing excess soil water is probably minimal (Swanston 1974). In the more xeric conditions that are normal for lodgepole pine forests, water use by trees may play an important part in maintaining soil mass stability (Swanston and Dryness 1973; Swanson 1981). The mitigation of excess water problems requires that the forest manager schedule timber removal in a manner to maintain high rates of water use by the remaining trees. This is the opposite effect to that desired to increase water yield, but the same hydrologic principles are involved in establishing the forest management practice to achieve either objective.

In this paper, my main emphasis is on the management of lodgepole pine forests to increase water yield rather than protection from erosion. I will discuss the general potential of this forest type for water yield improvement and briefly outline the manageable components of the water balance and the type of forest harvest that should produce maximum water yield. Then I will discuss several forest management strategies to affect significant water yield improvement, and the relationship of water augmentation forestry practices to those for other products. Lastly, I will outline the research needs that I see in the field of watershed management.

POTENTIAL OF LODGEPOLE PINE TYPE FOR WATER YIELD AUGMENTATION

Clear-cut harvesting of lodgepole pine forests is the established silvicultural practice throughout most of Canada and the United States. According to Anderson *et al.* (1976), the potential increase in water yield from patch clear-cutting Rocky Mountain lodgepole pine forests is 76 mm, which is equal to what could be achieved in the seemingly-wetter Engelmann spruce-fir type in the same region.

The changes in annual water yield that will result from clearcutting are relatively predictable because the physical characteristics of forests that most influence the hydrologic processes involved are crown density and residual stand arrangement. The abrupt edge between treed and clear-cut areas provides a physical barrier that influences snow distribution and shelters accumulated snow and low vegetation from wind and solar radiation. These effects are not dependent upon the absolute height of the surrounding trees. It is as possible to create a stand arrangement favorable for water yield increase in the short, overdense and small diameter stands that are common to fire-origin lodgepole pine as in those with higher economic value.

Excellent compendia or comprehensive reviews of the relationship of forests and forest harvesting practices to hydrological processes are available (Sopper and Lull 1967; Anderson *et al.*, 1976; Baumgartner 1981; AWRA 1983). I will cover only the salient points below.

Precipitation

Precipitation is the general term for all atmospheric moisture contacting the earth's surface. The two most important forms of precipitation are rain and snow. The total quantity of precipitation received by a watershed is governed by external conditions such as overlying air masses, adjacent water bodies and nearby mountains. Once precipitation is occurring, interaction with surface vegetation affects how it will be distributed among various loss, storage and transport component processes of the hydrologic cycle.

Interception and Areal Distribution

Part of the rain or snow that falls on a forested watershed adheres to the canopy. Some of this evaporates and some finds its way to the soil. That which evaporates is lost from streamflow. The amount actually lost is quite variable, depending upon the form and intensity of the precipitation, weather conditions during precipitation and the form and density of the forest canopy. Troendle and Leaf (1980) give a value of evaporation from intercepted precipitation of 15-20% of precipitation for coniferous forests.

Differential distribution of snow on the ground is an obvious occurrence in forests. More snow accumulates in clearings within the forest than under the canopy. The source of this snow was once thought to be purely reduced interception. More recent studies have shown that much of the increased accumulation is from the canopy of the surrounding trees (Hoover and Leaf 1967). A stand edge is a barrier to the smooth flow of wind. The turbulence near this edge induces snow accumulation along the border within the cleared area at the expense of accumulation within or under the canopy. This is a rather long-lived effect that continues to occur until the regrowth in the clearing is at least 3/4 the height of the surrounding stand (Gary 1979). The turbulence near stand edges may affect the ultimate surface deposition of rain as well as snow; however, I know of no studies that have demonstrated this.

The source of increased snow on the ground would simply be an academic argument if it did not influence how we must manage a forest to utilize this phenomenon to augment water yield. If the source were purely reduced interception loss after clear-cutting, then any size of clearing would accumulate more snow to achieve the desired effect. If the source is redistribution as well, then clearings must be interspersed within sufficient surrounding canopy to provide the snow that will ultimately accumulate in them.

Both processes operate in lodgepole pine forests. The type of snow that occurs throughout most of the lodgepole pine range is dry and cold. It is readily transported short distances by modest wind speeds. Maximum accumulation is found in clearings with maximum dimensions of 2-6 tree heights (Hoover and Leaf 1967; Golding and Swanson 1978; Troendle and Leaf 1981).

Once snow has been deposited on the ground surface, it may be physically displaced by wind action. During transport it is subject to loss by evaporation. While in place the snowpack is subject to ablation by either evaporation or melt. Both evaporation and melt are energy driven processes that are dependent upon temperature and turbulent (wind) transfer processes. The wind regime at a clear-cut surface is highly dependent upon the presence of surrounding trees. In Alberta, I have found that the wind speeds at 2 m height in the center of clearings greater than 15-20 tree heights across are similar to those present above the canopy, i.e., the surrounding forest has little or no effect on the windiness of these larger clearings. In clearings smaller than 6-10 tree heights across, the surrounding trees have a major effect as wind speeds are generally 1/10 to 1/20 of those measured above the canopy (Swanson 1980). The effect of clear-cut size on surface wind speed is a major determinant of transport and of evaporative loss from accumulated snow (Tabler 1975; Troendle and Leaf 1981).

Evapotranspiration From Treed And Cleared Areas

Evapotranspiration is a term describing the combined processes of direct vaporization from any surface (evaporation) and that which occurs mostly from within the stomatal cavities of leaves (transpiration). The importance of evapotranspiration in the water economy of a forest depends upon the type and time distribution of precipitation. The magnitude of evapotranspiration and the relative proportion of direct evaporation to transpiration are the hydrological loss components that forest cutting affects the most.

Transpiration is the major loss component from fully treed land. Baumgartner (1967) gives average values for the relative amounts of water lost by evapotranspiration as 10% direct evaporation, 30% as evaporation from from intercepted water and 60% as transpiration. Annual transpiration from a mixed lodgepole pine-Engelmann spruce stand in Colorado was estimated at 292 mm, 46% of the 639 mm precipitation occurring that year (Swanson 1975).

When a forest is rearranged from fully treed to partially clear-cut, the amount of water formerly transpired by the trees removed would seemingly be available as additional soil water or streamflow; however, water yield increases have usually been less than the estimated transpiration reduction. At least some of the water lost as transpiration prior to harvest is lost as either direct evaporation from the soil and vegetative surfaces of the clear-cut and/or transpiration by pre-existing understory or newly established vegetation in the clear-cut. Because energy availability and turbulent transfer processes determine the conditions for any vapor loss, one should expect the proximity of surrounding canopy (e.g. clear-cut size) to affect evapotranspiration from the newly-exposed surfaces of a clear-cut in much the same manner that snow ablation is affected. (For an example of the shelter effect on evaporation, see McNaughton 1983).

Cutting Pattern For Maximum Water Yield

The possibility of scaling clear-cut size as a multiple of surrounding tree height allows us to generalize a forest arrangement that should produce near-maximum water yield in mature as well as overstocked, stagnated lodgepole pine stands. This arrangement would be one in which 40-60% of the area was occupied by uniformly dispersed, clear-cut patches no greater than 2-6 tree heights in any dimension. Clear-cut patches of this size would accumulate and retain the snow redistributed from the surrounding canopy, and the surface of the clearing, whether snow or vegetation, would be protected from the full evaporative force of the above-canopy winds. This forest arrangement, although likely to produce maximum water yield, would not necessarily produce the most usable water because of the differing requirements of instream and downstream water users.

MANAGEMENT STRATEGIES FOR WATER YIELD AUGMENTATION

Both water and timber can be harvested from the same area. I am assuming that the existing timber management models are adequate to predict future yields if given site and rotation information. I will confine my remarks to water yield.

It is impossible to provide a general strategy of forest manipulation that will produce the desired water yield result in every situation. The needs of water users, which must be coupled with the physical and biological possibilities of the forest in a manner appropriate to the local climate and topography, are more diverse than those of the forest industry. One effective tool for deriving a site-specific management plan is a physically and ecologically based hydrologic system model, which estimates the effects on streamflow of various levels of forest cutting in that particular climatic and topographic situation (Ponce and Meiman 1983). Watershed research has provided a variety of such models to assist the manager in deriving site-specific management plans. I can't speak for forest hydrologists in the U.S. Forest Service, but those in the Canadian Forestry Service are more than willing to assist forest managers in the implementation and application of these.

The WRENSS Procedure For Estimating Annual Water Yields

A technique that is currently available and easy to use is the hydrology portion of the WRENSS (Water Resources Evaluation Non-point Sources in Silviculture) procedure devised by the U.S. Forest Service (Troendle and Leaf 1980). This procedure can be used to estimate the effect of a wide variety of forest-cutting practices on annual water yield. The information base from which it was developed includes most regions of the United States and Canada, and certainly those areas where lodgepole pine is of importance.

The data required to use this procedure are minimal. One needs only the seasonal precipitation value and an estimate of the basal area for the location in question in order to produce an estimate of both normal water yield (that which would occur in the absence of any cutting) and water yield under some pattern of clear-cutting. The Northern Forest Research Centre has used this technique extensively in Alberta and have found that it produces estimates of normal water yield within 10% of that measured. The estimates for treated water yield are consistent with those observed in experimental situations.

The water yields that would result from complete clear-cutting to almost any mixture of partial cutting can be estimated with WRENSS. The most reliable results appear to be obtained when clear-cut patches are less than 15 tree heights in any dimension. Results for larger clear-cuts may not be as reliable because the surrounding trees have less influence over the microclimate at their surface than in those clear-cuts less than 15 tree heights across. Estimates for these larger clear-cuts should be based on a knowledge of the altered microclimatic parameters, particularly wind speed. At present, there is no provision in the WRENSS procedure to input such local data, even if it were available. For most lodgepole pine stands, the trees are in the vicinity of 20 m tall; therefore the procedure functions best with clearings less than 9 ha in area. I consider the estimates for clear-cuts 15 tree heights across to be applicable to much larger ones if it is clearly understood that these are quite likely overestimates of water yield in windy locations.

The hydrology portion of WRENSS (Troendle and Leaf 1980) consists of 173 pages of text and graphs. Estimates are made using a "cookbook" approach through the creation of tables from graphical extractions. To say that potential users have been intimidated by the procedure would be an understatement! It took me several hours to work through it, and I am very familiar with both the research underlying the publication and the hydrologic processes involved.

At the Northern Forest Research Centre, we have digitized the graphs and prepared an interactive FORTRAN program that accomplishes the WRENSS estimates. The time required to examine a new situation is about 10 seconds using a mainframe computer or about 3 minutes on an IBM compatible personal computer. The program prompts for the necessary inputs and supplies defaults if the user desires. Table 1 is an example of the output.

Only the annual total water yields are valid estimates. The WRENSS procedure calculates intermediate values called "seasonal water yield." These calculated water yields may be positive, zero, or negative, depending upon the precipitation and evapotranspiration occurring during that season. The breakdown of WRENSS output into seasons is purely for the estimation of evapotranspiration loss from seasonal precipitation. The seasonal water yield values must be summed algebraically to determine an annual water yield total.

Time of Water Yield

I have mentioned several instances where the time at which a water yield increase might occur would be important to resident or downstream users. Another instance would be in evaluating the channel stability criteria used by Region 1 of the USFS. Average monthly flows are used in the channel stability criteria. However, Harr (1981) points out that the size and duration of instantaneous flow rates, rather than mean monthly or annual rates, are the principal channel-shaping events.

The input data used in the WRENSS procedure is seasonal precipitation and this technique cannot be used to directly estimate peak streamflow for any time period. The WRENSS handbook (Troendle and Leaf 1980) is somewhat misleading in this respect as it contains a section on estimating the portion of annual yield that would occur during a 7-day period. The technique that the authors used to obtain these 7-day values in snow dominated regions was simply one of apportioning the annual flow among 52 consecutive 7-day periods in the same proportion as a local hydrograph or the one that was used to generate the procedural example (Fool Creek on the Fraser Experimental Forest in Colorado for WRENSS hydrologic region 4). Unless one has prior knowledge of the effect of cutting on flow timing in his situation, he has no basis on which to select a particular hydrograph for the 7-day apportionment. A similar procedure is used to estimate flow duration in rain dominated regions, and the same arguments apply to its use there too.

At the present time, one must use a hydrologic model with hourly or daily values of precipitation to simulate daily flows if he needs an estimate of instantaneous peak flows. This could be the same hydrologic model that Troendle and Leaf (1980) used to produce the WRENSS procedure. Several years of streamflow and climatic data are required for the calibration and operation of this model (Leaf and Brink 1975). There are very few situations in which these data would be available in the absence of a long-range plan to provide them.

Table 1.—WRENSS estimates of annual water yield changes resulting from patchcutting 50% of a watershed in 4 ha blocks.

```
HYDROLOGIC REGION #6
NAME OF BASIN: ALBERTA LODGEPOLE PINE
AREA OF BASIN (SQ.KM)= 1.00
% IN N, E+W AND SOUTH ASPECTS: 33, 33, 33%

******* INPUTS FOR ASPECT: NORTH
PRECIPITATION (CM): 11.4
PRECIPITATION (CM): 20.6
PRECIPITATION (CM): 18.5
TREE TYPE: LODGEPOLE
BASAL AREA OF STAND: 35 SQ M/HA
MAXIMAL BASAL AREA: 35 SQ M/HA
% OF ASPECT CUT: 50
AVERAGE AREA OF CUTS: 4 HA
BASAL AREA IN CUTS: 0 SQ M/HA
HEIGHT OF TREES: 20 M
WINDWARD LENGTH OF CUTS: 10 tree heights

******* INPUTS FOR ASPECT: EAST+WEST
INPUTS IDENTICAL TO THOSE OF PREVIOUS ASPECT
******* INPUTS FOR ASPECT: SOUTH
INPUTS IDENTICAL TO THOSE OF PREVIOUS ASPECT

SEASON: OCT01-FEB28:
              NORTH           EAST+WEST          SOUTH
          FOR      OPEN     FOR      OPEN     FOR      OPEN
PRECIP    9.4      13.4     9.4      13.4     9.4      13.4
ET        3.3       2.2     4.8       3.1     6.6       4.2
FLOW      6.1      11.2     4.6      10.2     2.8       9.1

SEASON: MAR01-JUN30:
              NORTH           EAST+WEST          SOUTH
          FOR      OPEN     FOR      OPEN     FOR      OPEN
PRECIP   17.1      24.1    17.1      24.1    17.1      24.1
ET        7.2       7.4    10.9      10.5    15.8      18.7
FLOW      9.8      16.7     6.1      13.6     1.2       5.4

SEASON: JUL01-SEP30
              NORTH           EAST+WEST          SOUTH
          FOR      OPEN     FOR      OPEN     FOR      OPEN
PRECIP   18.5      18.5    18.5      18.5    18.5      18.5
ET       19.3      13.6    19.3      13.6    19.3      12.2
FLOW     -0.8       4.9    -0.8       4.9    -0.8       6.3

YEARLY FLOW CM: 18.5 **** CU DAM: 184.5
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Water Management Options

There has been a lot of talk about cutting forests to augment water yield, but little or no action taken to implement a management plan (Arizona Water Commission 1974; Ffolliott 1974; Hurst 1974; Northwest Hydraulics Consultants Ltd. 1977; Hibbert 1981). The Government of Alberta is currently investigating the possibility of conducting a pilot scale forest harvest of a watershed greater than 100 km^2 in area specifically to increase the annual yield by 15% or more. Perhaps they have the cart before the horse, but one of the questions that keeps cropping up in their discussions of this pilot project is "how will a management plan to augment water yield affect commitments of timber to the local forest industry?" This is a valid question.

In order to get some idea of the type of management plans that could be imposed in Alberta, I have used the WRENSS procedure to estimate the water yield that would occur if a 100 km^2 watershed was harvested in its entirety into an even number of clear-cut and treed patches ranging from 0.16 to 16 ha (Table 2). I then used these data to ascertain the annual water yield from the watershed upon complete implementation of each of the following three forest management options:

a) water considered as the only product,
b) water as an equal coproduct with timber and,
c) water as an unimportant by-product of normal timber harvesting operations.

I have also included the water yield results from the forest management scheme proposed by Leaf and Alexander (1975) for the Colorado-Wyoming area.

Table 2.–Estimated annual water yields from a 100 km^2 lodgepole pine watershed in the Alberta foothills, using the USFS WRENSS technique for snow dominated hydrologic region 6, with annual precipitation of 505 mm, tree height 20 m, basal area 35 m^2/ha, with precipitation seasonally distributed as in Table 1. The patchcuts have been considered as squares, n[tree heights (H)] on each side. Y indicates annual yield in mm, I indicates increase above untreated yield.

Patch Size				ASPECT					
area	height	North		East-West		South		All	
ha	**H**	**Y**	**I**	**Y**	**I**	**Y**	**I**	**Y**	**I**
uncut	0	197	0	143	0	75	0	138	0mm
.16	2	240	43	194	51	121	46	185	47
.64	4	241	44	194	51	123	48	186	48
1.44	6	241	44	195	52	125	50	187	49
4.00	10	240	43	193	50	120	45	184	46
9.00	15	226	29	179	36	106	31	170	32
20.00	20	220	23	174	31	102	27	165	27

Water The Only Management Product

Timber harvesting is used solely as a tool to create and maintain a desirable arrangement of trees and clear-cut patches to maximize annual water yield. The clear-cut patches would have maximum dimensions of 2-6 tree heights and be kept free of tree-type regeneration in order to maintain water yields at the highest level. Timber cutting would be conducted in the residual blocks on a selection or group selection basis in order to maintain the stability of the treed patches which provide the contributing canopy and edge turbulence necessary for maximum snow accumulation and protection of the clear-cut surfaces from wind action.

The water yield increase under this option would reach a maximum of 49 mm as soon as completely implemented. It would remain at this level in perpetuity.

Water As An Equal Coproduct With Timber

The size and arrangement of the clear-cut patches would be the same as in option 1; however, regeneration would be encouraged in the clear-cut blocks. Under a 100-year rotation, the residuals would be removed starting at year 50. This option would not disrupt the flow of timber products.

The water yield increase under this option would reach a maximum of 25 mm at year 50. Thereafter it would remain constant in perpetuity.

Water As A By-product

Cut blocks would be 9 ha and larger. Residuals cut 20 years after the first entry. This option would affect neither the economics nor flow of timber products.

The water yield increase under this option would reach a maximum of 16 mm at year 50, and remain at that level in perpetuity.

Leaf and Alexander Timber And Water Model

In this scheme, all of the old-growth timber would be harvested from the area in 120 years. At 30-year intervals, approximately one-third of the area would be harvested in a number of evenly distributed, 5-8 tree height (maximum dimension) openings arranged in such a manner at to complement the natural landscape. At appoximately 10-year intervals, the density of stocking on some of the previously cutover areas would be reduced to one-fourth of the natural old-growth cover density. The expectation for this scheme is a stand of 2500 stems/ha at age 30 years.

The water yield increase under this option reaches a peak at age 61-70 with cyclical fluctuations occurring at each entry interval (Table 3). The average annual increase over the 120-year rotation is 54 mm.

Advance Preparation For Watershed Management

It is my view that the purpose of management is to foresee events and to prepare plans to allow for them. If timely water is foreseen to be a future problem or if peak flows are thought to jeopardize channel stability, then it is up to the forest manager to start getting the necessary data to conduct a proper hydrologic evaluation of any cutting practices proposed for the area. All predictive techniques in hydrology are based on the availability of precipitation, streamflow, solar radiation, air temperature, air humidity, and wind speed data for the areas concerned.

Watershed researchers are continually deriving new or improved models, but the input data for these models has not changed significantly. The forest manager should not postpone or delay the acquisition of these data in anticipation of better models in the future.

Table 3. – Projected changes in annual water yield resulting from timber harvesting in lodgepole pine, Deadhorse Creek planning unit, Fraser Experimental Forest, Colorado (Leaf and Alexander 1975).

Interval years	Water yield increase, by treatment I	II	III	IV
0-10	44 mm			
11-20	44			
21-30	33			
31-40		62 mm		
41-50		58		
51-60		39		
61-70			79 mm	
71-80			73	
81-90			54	
91-100				72 mm
101-110				50
111-120				35
Average increase over 120-years: 54 mm				

RELATIONSHIP OF WATER MANAGEMENT FORESTRY TO OTHER FOREST USERS

Recreation

The perception of what constitutes proper recreational land is as varied as the number of users. I am sure that any one who insists that the land must look "natural" would not be happy with any forest management scheme. However, an area managed solely for water, (option 1 above) could be made to look "park-like" by creating irregular shapes and sizes of clearings. If the residual forest were maintained through some form of selection silviculture, as suggested, then the access necessary to carry out silvicultural operations would benefit the recreational user as well.

Wildlife Habitat

Option 1 above would probably be close to optimum management for wildlife habitat (Reynolds 1972). The clearings could be revegetated with browse species rather than trees. The quantity of edge and cover would remain constant and close to the maximum that one could create with any type of clear-cutting.

The remaining two options discussed above would be of lesser benefit to wildlife. The desire to regenerate the clearings with trees would reduce the browse possibility; however the amount of edge and cover would be large and maintained at a relatively high level throughout a rotation.

Intensive Forestry

Under most of the options outlined above, soil moisture would be significantly increased due to the increased snow accumulation and reduced evapotranspiration demand. Dahms (1971) has shown that under some circumstances, increased soil moisture does result in increased volume growth. According to Mogren and Dolph (1972), all factors significantly correlated with site index are related to the availability of water to trees. One might thus presume that the site index of these smaller clearings, where snow accumulation is increased for 50 years or more, would be increased by one or more level.

Obviously the water management only option discussed earlier would interfere with forest production. In the residual treed patches, the soil moisture available to trees near the clear-cut edges would be greater because of the greater amount of soil water in the clearings. This soil moisture would be available to a large portion of the residual stand because of the vast amount of edge that this type of patch clear-cutting would create. The productivity of the residual stands might also be improved through a program of replacing them with genetically superior stock.

In the second option, the possibility of translating these differing site conditions into improved growth and shorter rotations would probably depend upon the type of tree used to regenerate the clear-cuts. The local logepole pine is a conservative species that is well-adapted to the cold climate and relative dry site conditions prevalent in the Rocky Mountain interior. There is a wide range of variability in the growth rate of natural reproduction. Rehfeldt *et al.* (1980) estimate that simple mass selection techniques would produce gains in height growth of 11-45%. Unless one were to carry out extensive and very selective thinning of natural reproduction, selected or genetically improved stock would probably be required to take advantage of the changed regeneration and growing conditions that would be created under a system of intensive water management forestry.

RESEARCH NEEDS

There really aren't any outstanding problems that would prevent immediate application of some form of forest management specifically designed to augment water supply. There is a need to provide better quantitative means of evaluating or predicting the influence of wind on snow ablation and evapotranspiration from the surface of clear-cuts larger than 6-10 tree heights across, which would allow more confidence in the use of the larger clear-cuts in areas where the economics of wood products precludes the extra roading and management costs associated with the smaller ones.

There is a need for a practice of watershed management to develop. Without such a practice, there is no feedback to research of questions relevant to the forest manager. Watershed management research is in danger of repeating old experiments simply to provide an education for the researcher. Presumably, pilot studies are a first step toward such a practice. It will be interesting to see if those proposed in Alberta and Arizona are ever implemented.

There is a need for continuing forest hydrology research and the developments of techniques to interface hydrologic findings with silviculture. For example, research has established that both warm and cold micro-climates can be created through patterned forest harvest (Anderson 1963; Golding and Swanson 1978). Anderson's wall-and-step forest can be created with clearcutting progressing in a south-to-north direction to cause either early snowmelt in a warm microclimate at the south-facing cleared-treed area interface, or cut in the reverse direction to delay snowmelt in the shaded and colder north-facing environment. The microclimate that these patterns create should be examined with respect to their influence on regeneration and growth.

Lastly, there is a need for a physically-based physiological method to interface forest hydrology research findings, with respect to microclimate and soil moisture alteration, and tree growth and yield models. The term "site" that is now used is too vague and includes too many climate, soil, and biological characteristics to be useful in a physical-physiological context. Such a method should enable the tailoring of microenvironments specific to the regeneration, growth, and survival requirements of selected or genetically improved trees.

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HARVEST AND UTILIZATION

HARVESTING SYSTEMS FOR LODGEPOLE PINE FORESTS

Michael J. Gonsior and Leonard R. Johnson

ABSTRACT

The alternatives available for harvesting lodgepole pine and the associated cost and environmental effects mainly depend upon stand and terrain characteristics, silvicultural prescriptions, road system characteristics, and proximity and types of wood products markets.

Harvesting costs per unit of volume increase at an increasing rate with reductions in tree size. Many systems designed for commercial timber stands prove oversized and costly in smaller lodgepole pine. Reductions in equipment size do not achieve a corresponding cost reduction sufficient to keep the cost per unit of output at a constant level. Mechanized systems that can produce at levels high enough to offset piece size are limited by both terrain and silvicultural prescription. Steep slopes may require manual felling, which can hamper subsequent mechanization. Thinning may also limit the use of highly mechanized equipment. In selective cuttings, costs may be reduced by bunching to pre-selected trails and using high capacity equipment from that point on.

INTRODUCTION

Nearly 20 years ago, McIntosh and Csizmazia (1965) wrote regarding lodgepole pine in British Columbia:

> It is a suitable species for lumber, veneer, pulp, railing ties, poles, posts, etc., and compares in quality with similar products from other species.
>
> However, its small size has to date prevented it from assuming an important role in the forest economy . . . . This situation is expected to change substantially in the near future as sustained yield management policies are implemented and the full potential of lodgepole pine is utilized.
>
> Tree size is an important factor affecting harvesting costs, and the harvesting methods and equipment designed to handle the larger trees such as spruce and Douglas-fir are not necessarily suited to the economic harvesting of smaller trees such as lodgepole pine.

Indeed, significant changes in harvesting technology have occurred in the intervening years. Nevertheless, the rate of harvest of lodgepole pine apparently still remains below its potential. According to Barger and Fiedler (1982):

> An immediate and urgent concern in the Northern Rocky Mountains is the recovery and use of beetle-killed lodgepole pine, and the implementation of harvesting treatments to reduce further insect mortality . . . A major barrier to achieving effective multiresource protection and management is the present lack of technically and economically viable utilization alternatives for the material that should be removed.

In this paper, we will briefly review alternatives for harvesting lodgepole pine and discuss the harvesting costs. Harvesting is considered herein to entail all processes and activities associated with clearing or thinning a timber stand and delivering some or all of the resulting wood fiber to wood products manufacturing facilities, excluding road construction and maintenance as well as any subsequent site treatments such as slash piling and/or burning. This is not to deny the importance of road and postharvest site treatment costs to decisions in particular circumstances; rather, it is for expedience and to enable generalization that we so limit our definition of harvesting.

Many factors affect harvesting productivity and cost, but we will consider only tree size, ground slope, cutting prescription (clearcutting versus thinning), and average distance from stump to roadside (skidding or forwarding distance).

This paper will neither recommend harvesting systems that should be used, nor provide a basis for estimating harvesting costs in particular circumstances. Our assumption is that the reader is not a harvest system expert or designer, but may deal with such specialists on occasion. The specialist's analysis would be too long and detailed to pursue here.

TIMBER HARVESTING ALTERNATIVES

Systems for harvesting lodgepole pine range from those incorporating manual felling and wheeled skidders with chokers to those involving complete mechanization. System choice is obviously influenced by the intended product, but will also depend on factors such as size of potential harvest tracts and the probability of having a long-term market for the product. The number of specific machine combinations available is nearly infinite, but figure 1 outlines the general scope of systems available. The systems become increasingly mechanized. Equipment represented by the highly mechanized options at the bottom of the figure are in some cases prototype machines.

The first two systems represent basic options where manual felling is followed by wheeled skidding with chokers. Limbing, bucking, and topping can be performed in the woods or at the landing. Location of the limbing will probably depend on slash treatment. Leaving tops and limbs in the woods may be required to achieve natural regeneration of a lodgepole pine stand. Costs are extremely sensitive to average piece size and

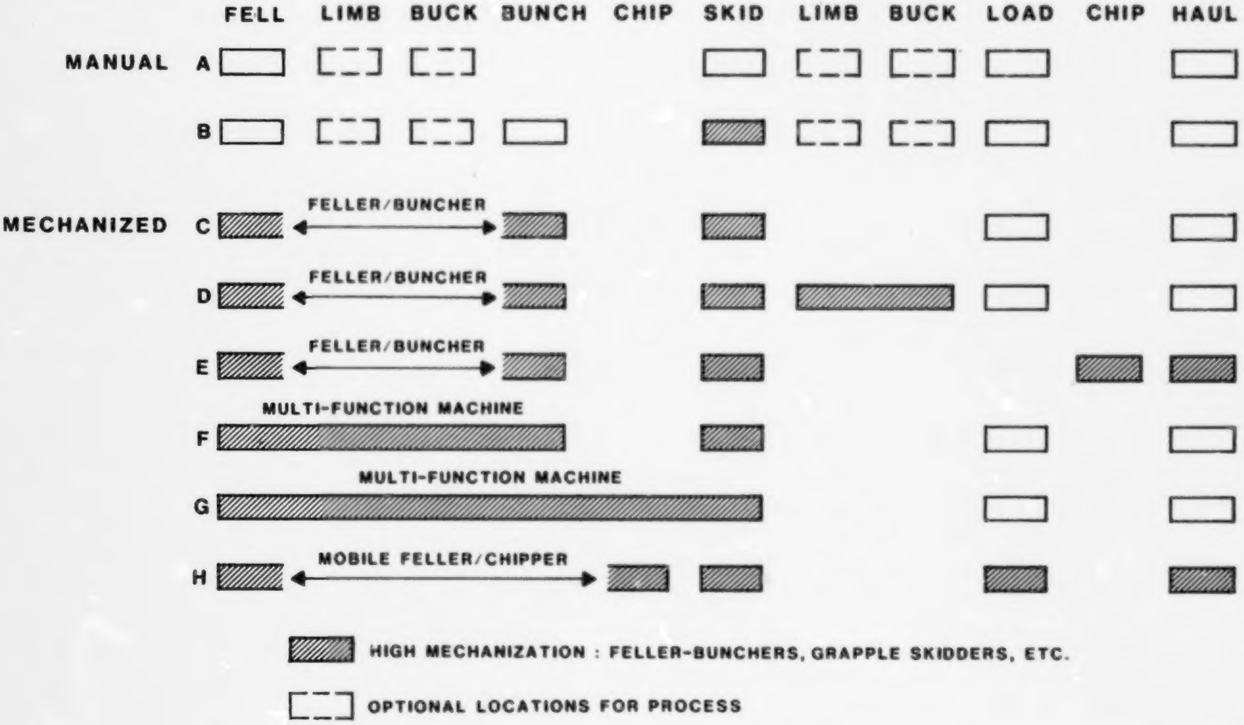

Figure 1. – General scope of available harvesting systems.

density. Felling costs per unit of volume may be lower than for some types of mechanized operations, but a penalty is paid in skidding. Skidder operators must locate and hook each piece. The process is time consuming and makes it difficult to fully utilize machine capacity.

Skidding loads can be maximized by a separate bunching operation. In some short-wood operations where trees may be bucked to 1.37 to 2.44 meters (4.5 to 8 foot lengths), this might be done manually. Other options include the use of equipment matched to small timber. These could include small wheeled or tracked skidders or portable cable winches. Winches could add from $3,000 to $12,000 to the capital cost of a system. Small skidders could add from $15,000 to $30,000 to the system cost. This option would probably be considered only in situations where the cutting prescription or the terrain restrict the use of mechanized feller-bunchers. Accumulation of material into skidder-sized loads at a single location will allow effective use of grapple-skidders. The costs of bunching must be offset by savings in skidding.

Bunching can also be accomplished in the felling step through the use of machanized feller-bunchers. Costs and trafficability of the units range from cheaper ones limited to 10 to 15 percent slopes, to more expensive units that can negotiate 50 to 60 percent slopes. Slope and timber size have been the primary constraints to applications of mechanical felling and bunching.

The average size of lodgepole pine falls well within the diameter limits of most machines. Newer model feller bunchers, such as the Timbco and Spyder[1], can also negotiate slopes of 50 to 60 percent. Equipment that can bunch timber on steep slopes will open more areas to mechanized harvest and will have direct application to many lodgepole pine areas.

Bunched trees can be handled most efficiently with some type of grapple skidder. Operations at the landing will generally need to be adjusted or mechanized to keep up with the high volume of flow created by mechanical felling and bunching. One option involves direct loading of whole trees onto trucks. Tree tops can be cut from the boles after the truck is loaded. The system provides efficiencies at the landing by eliminating the topping and limbing step from the principal wood flow. The process may require special permits to exceed legal load limits and to haul long loads, and a mill designed to handle small-diameter material.

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[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the University of Idaho of any product or service to the exclusion of others that may be suitable.

Loading could be a handicap in this option. It requires many small stems to build a full load. Preload bunks could be a useful addition to the system. The bunks are positioned on a landing and could be loaded by grapple skidders as trees are delivered to the landing. Trees could be topped while in the bunk. Loading onto trucks involves lifting the bunk load, backing the truck under the bunk, and lowering the load onto the truck. The loading operation would be speeded up and a separate loader would be eliminated from the system. Bunks may require landings that might otherwise be needed.

Lodgepole pine lends itself to a mechanized production process better than many other species. Most lodgepole pine trees are relatively free of limbs, and the limbs present are often concentrated toward the top of the tree. In cases where more extensive or precise limbing is needed, mechanized delimbing and bucking can be conducted at the landing. Various methods of delimbing have been attempted throughout North America.

The chain-flail delimber is a wheeled machine that travels the length of the tree and knocks off limbs by means of rotating chains. Gate delimbers have been used successfully in some areas. Material is pulled forward through a metal "gate" with vertical bars. The trees are then forced back through the gate and limbs are broken off in the process. Both delimbing techniques can be time consuming and, at times, ineffective. Delimbing can often be a bottleneck in a production system. The time required per tree can be disproportionately high for small trees. Mechanization of the felling function will generally require mechanization of the limbing function.

Two general types of equipment are available for mechanical delimbing and bucking at the landing. (These include slashers, tree processors, and harvesters.) One type of machine occupies a fixed position at a landing. Material is delivered to the machine, loaded on its feed chain, and fed through delimbing knives and a bucking saw. The operator has a good view of the log for bucking. Slash and logs can accumulate rather rapidly around the delimber and must be constantly pushed away. The second kind of machine is often called a boom-type delimber. The machine travels to the decked logs, picks them up one or two at a time, and strips the limbs. Slash accumulation is not as severe as with the fixed position delimber. Such machines can add from $180,000 to $225,000 to the capital investment of a system. If the delimbing and bucking step can be bypassed or reduced to a single topping cut, capital requirements for a mechanized system can be reduced substantially.

Delivery of whole trees to the landing using feller-bunchers and grapple skidders could be followed by a chipping step rather than loading. Whole-tree chippers have been effectively used where there is a good market for the product. Utilization of the available woods fiber is increased by chipping tops and limbs with the bole. A decision to chip in the woods can obligate all the wood from the site to a single product. It may not be feasible to sort material into products before chipping. Chipping in the woods will also require an assessment of the road network to the site. Curve radii must be longer and roads wider on roads that will be used by trucks with chip vans. Landing size also becomes critical.

The primary factor limiting increased recovery of the lodgepole pine resource through chipping is a viable market for the product. Although the chip meets the physical requirements set up by pulp mills, the presence of bark causes the material to be downgraded from a clean pulp chip to the category "dirty chip" or "hog fuel." The price paid for hog fuel can be one-fourth the price paid for clean pulp chips.

If a good market develops for whole-tree chips, other options will become available for processing lodgepole pine stands on relatively flat terrain. Processors capable of traveling onto the site, cutting and chipping slash are in the prototype stage (Koch and Savage, 1980). Such machines operate like agricultural combines. Their use and further development are hindered only by the market values of the chipped product. Separation of bark from wood chips is a possibility for improving whole tree chip values, and is being developed.

Mechanization of the limbing, topping, and bucking functions could be combined with felling and bunching in a multifunction machine. Machines of this type have been developed and used in Europe. The Timberjack Model 30 and John Deere 743 are examples of multifunction machines manufactured in North America. The Timberjack contains a bunk for deposit and forwarding of the trees. The John Deere is designed to bunch trees on site for skidding with grapple skidders. Machines capable of performing several functions are often limited to gentle terrain. Their use will leave tops and limbs in the woods. This may be desired for subsequent regeneration. The product delivered to the landing should require no additional processing and could be effectively delivered to preload bunks.

EFFECT AND LIMITATIONS ON MECHANIZATION

Mechanized harvesting systems are currently available to effectively harvest the lodgepole pine resource. Their use has been constrained by the lack of markets for the products produced by the system. Mechanization can be effective in reducing harvesting cost in dollars per unit of volume. Although hourly costs increase substantially, the production rate in volume per hour also increases.

Boyd and Novak (1977) state, however, that:

> When all factors of engineering, design, operator, mechanic, and supervisor achievement are at near-ideal levels, any of the presently available concepts of logging systems appears to have the potential to produce wood at costs equal to or better than conventional manual systems. With poor achievements in hardware or

operation, any concept currently available can result in wood costs higher than conventional systems.

> No logging system currently available can miraculously reduce wood cost. Good concepts, combined with effective application, superior design, low maintenance costs and effective operation by trained and skilled operators and mechanics working with top quality tools in best facilities, can achieve significant savings in wood cost, higher productivity, and less investment per cunit produced than conventional systems.

Higher levels of mechanization will require greater attention to maintenance programs, operator skill and knowledge, and the planning required for operations.

Cubbage and Granskog (1982) and Cubbage (1982; 1983) analyzed several systems available for harvesting pine in the southeastern United States. Conditions on many of the loblolly pine sites resemble those encountered when harvesting lodgepole pine. Mechanized felling and bunching, followed by grapple skidding and whole-tree chipping, resulted in the lowest cost per unit of volume. The low cost reflected high production, increased yield from the stand, and elimination of delimbing. Use of a feller-buncher and mechanical delimbing in a whole-tree operation resulted in costs that were 12 percent higher than whole-tree chipping in one instance (Cubbage and Granskog, 1982) and 28 percent in another (Cubbage, 1983). A manual operation involving tree-length logging had costs that were 21 percent higher than whole tree-chipping in the first case and 63 percent higher in the second.

Mechanization of a harvesting operation can reduce basic harvesting costs, but other factors must be considered. Investment costs for a mechanized operation are very high. Cubbage and Granskog report a cost breakdown of 60 to 65 percent for equipment and 35 to 40 percent for labor in mechanized systems. The percentages are reversed for their manual, tree-length systems. Operators with high investment costs require a steady source of raw material and a reliable market to justify the high capital expenditures. Lending institutions may require signed contracts assuring both the supply and the market. Conditions reflecting a high risk in either area will not attract operators with mechanized, specialized equipment. Risks are likely to be taken by firms that can get in and out of production with relative ease. These will often involve systems with a high labor component.

The minimum feasible size of harvested tracts becomes larger as the degree of mechanization increases. Moving costs for systems increase with the size of equipment and the degree of mechanization. Cubbage (1982) develops minimum tract sizes for a variety of systems. Highly mechanized systems require a harvest area of at least 40 to 49 hectares (100 to 120 acres) for optimum harvest costs. A manual, tree-length system achieves lowest costs when the area is at least 24 hectares (60 acres).

Harvesting technology improvements in the recent past have provided equipment that can effectively fell and bunch trees on a wide variety of slopes. Bunching allows effective skidding at relatively short distances with conventional rubber-tired skidders or fast-track machines. Tracked machines with high travel speeds and steep slope feller bunchers open areas to harvest that were previously ignored because of the costs of felling and cable yarding. Capability for bunching large volumes of delimbed and bucked trees creates opportunities for the use of long-distance forwarders. Use of these machines could reduce access costs to some areas by increasing the spacing of haul roads. Technology appears to be available to effectively process the small trees typically found in lodgepole pine stands. Increased utilization currently seems to be limited by the lack of reasonable markets for small logs or dirty chips.

HARVEST COST VERSUS PRODUCT VALUE IN SMALL TIMBER

Tree or piece size is one of the most important factors affecting harvesting productivity and costs, whether with systems using manual felling methods (Hannula, 1971) or highly mechanized systems (Lanford, 1983; Aird and others, 1970). This general relationship is as shown in figure 2 (after Lanford,

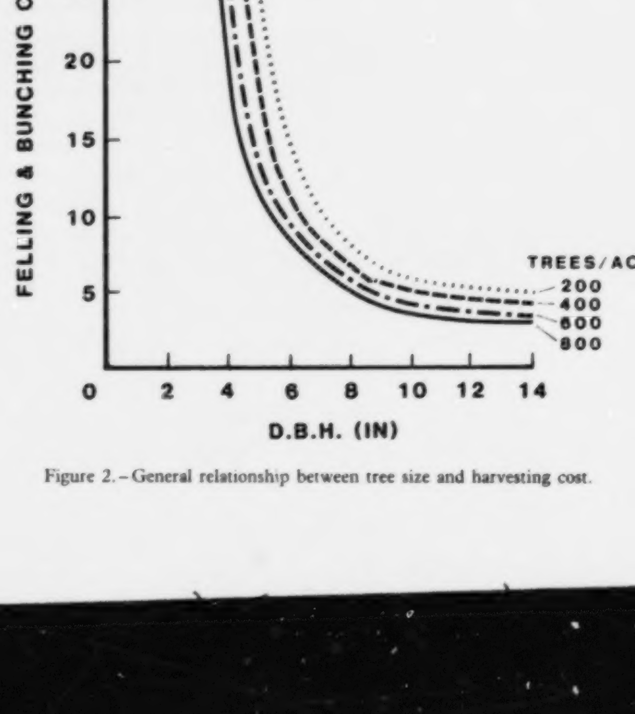

Figure 2.–General relationship between tree size and harvesting cost.

1983). This relationship holds for any particular system only within the range of tree sizes for which the system is designed.

In general, as stand densities decrease and as skidding or forwarding distances increase, harvesting costs also increase (Lanford, 1983; Csizmazia and McIntosh, 1964; Bartholomew and others, 1965; Arvidsson and Spahr, 1980). When thinning is called for instead of clearcutting, the increasing cost effect of reduced stand density (that is, density of trees to be removed) is amplified by the difficulty of having to work among residual leave trees. In the extreme, there is an upper limit on residual stand density for each harvesting system, above which it is impossible to operate.

Figure 3 (after Brown and others, 1982) combines the general harvesting cost versus tree volume relationship of figure 2 with the general relationship of tree value versus tree volume. Figure 3 depicts what is considered to be the principal problem in small timber, such as lodgepole pine – that the cost of harvesting equals or exceeds the value of the timber resource due to small average tree sizes. According to Barger and Fiedler (1982), lodgepole pine sawtimber commonly averages 22.86 to 30.48 cm (9 to 12 inches) d.b.h. – well within the concept of "small timber." Indeed, one goal of mechanization is to lower the harvesting cost curve of figure 3, shifting the marginal tree size to the left or downward.

Illustrations such as figure 3 probably oversimplify reality, and may lead to erroneous conclusions. The relationships apply at a particular point in time and represent overall averages based on the level of consumption at that point in time. Note that the low values occurring near the small end of the average tree volume scale are the averages of a lot of fiber used as hog fuel and a minor amount of fiber used for very high value products such as fence rails and tree stakes. There may be no higher value per unit volume for lodgepole pine, for example, than that of tree stakes 5.08 cm (2 inches) in diameter retailing for $0.82 per meter (25¢ per foot) – the equivalent of over $353 per cubic meter ($1,000 per cunit). This market is restricted, however, to relatively small quantities annually.

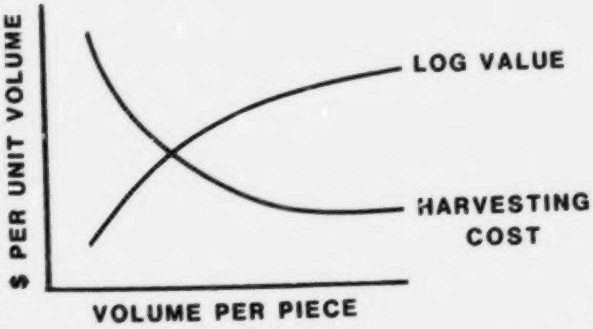

Figure 3. – General effect of average volume per tree on harvesting cost and on tree value.

In a particular situation, choices such as the production of chips only, or a combination of chips and roundwood, face a timber purchaser or logging firm. For example, Ince (1982) reported the delivered cost of chips averaged $39.13 per ovendry metric ton ($35.49 per ovendry ton) when only chips were produced in a 1979 demonstration harvest. When a combination of chips and roundwood was produced, the delivered cost of the roundwood logs averaged $63.05 per ovendry metric ton ($57.19 per ovendry ton), while the cost of the chips averaged $52.02 per ovendry metric ton ($47.18 per ovendry ton). The choice would be determined by profits, not costs alone. There is not just one harvest cost versus average tree volume relationship, as shown in figure 3, just as there is not just one value versus volume relationship. In any particular circumstance, it is the difference between average value and average cost, or profit, that determines what harvesting technology will be chosen – not cost or value alone.

What happens when technological improvements result in a lowering of the harvest cost curve? If, at current prices, there is unsatisfied demand, then one would expect a lowering of the cost curve in figure 3 to not only increase the volume harvested, but also to reduce the marginal tree size. Previously uneconomical stands should become harvestable. If at current prices there is no unsatisfied demand, only a decline in price would increase consumption. Therefore, the value curve in figure 3 would have to be lowered. If both the harvest cost and tree value curves in figure 3 are lowered, the marginal tree size may remain unaffected, as may the difference between value and cost. Even so, the total volume that can be harvested and utilized should increase if owners or managers of lodgepole pine forests are willing to sell at current stumpage prices.

Improvements in lodgepole pine harvesting technologies probably can be applied in other forest types. Thus, the competitive position of lodgepole may not be changed by harvesting systems improvements and could even be worsened.

Whether the demand for lodgepole pine would be affected significantly by changes in price deserves study. If, for example, a breakthrough in harvesting technology would permit an average reduction in mill delivery costs of, say, 10 percent, would the demand be increased appreciably? If not, then lodgepole pine harvest would not be increased. The average of stumpage receipts could be increased or the average of mill-delivered prices could be reduced, which are worthwhile outcomes that justify technological improvements; but, the goal of increased lodgepole pine consumption might not be reached.

THE STEEP SLOPE PROBLEM

Feller-bunchers for steep terrain, such as the Timbco, have already been mentioned. However, in much steep terrain, cable yarding must be used. Cable yarding is more expensive than wheeled or tracked skidding or forwarding. Murphy (1979), for example, reported cable logging cost to be about double that of conventional flat-country logging for both clearfelling and thinning. It is also difficult and expensive to handle and process whole trees in the confines of narrow roads in steep terrain. The search continues for good solutions to this problem. The higher harvest costs experienced in steep terrain will continue to favor small-timber operations in gentle terrain.

THE ROADLESS TERRAIN PROBLEM

In western North America, there remain sizable tracts of lodgepole that are not yet roaded. Given the marginal economic status of much of the lodgepole pine already roaded, it may seem ludicrous to even consider the unroaded situations. Nevertheless, there is interest in finding ways to extract timber from unroaded terrain. Unroaded areas present opportunities to match road design and spacing with long distance forwarding options. For example, existing off-road forwarders can economically move half-truck loads for distances of 1 to 2 kilometers.

Among the ideas being pursued are the Helistat (Piasecki, 1978) and Cyclocrane (Martin, 1979) for which roadless felling and bunching technologies will be needed. Also, long-reach cable forwarding systems may become feasible.

CONCLUSIONS

Most systems can be categorized as either full-tree, tree-length, or short-wood systems. With respect to costs, Boyd and Novak (1977) concluded there was no important difference between the potential of full-tree systems and tree-length systems, and that system selection is likely to depend primarily upon a detailed analysis of performance achieved by specific machines, rather than upon the type of system or on system concept.

Mellgren (1978) analyzed six systems – two short-wood and four tree-length – and concluded that there was no significant difference in the potential costs per cunit between the different systems. He noted that the user must base his selection of system on the quality of the machines and the training and service provided by the manufacturer.

From the standpoint of the lodgepole pine silviculture, short-wood and tree-length systems would seem advantageous because such systems leave limbs and tops on the forest floor as a seed supply source (McClelland, 1970). The world's forest industry, however, generally considers full-tree logging to offer the greatest potential for totally efficient tree harvesting (Hamilton, 1980; Mandzak and others, 1983). Indeed, Mandzak (1984) points out that if falling and bunching occurs in the summer and bunches remain in the heat for a few days before skidding, the lodgepole pine cones will usually open. Also, during skidding, many cones are knocked off and subsequently open in the summer heat. If the situation in Eastern Canada is similar to that in the lodgepole forests of Western Canada and the United States, one would expect a decline in the use of short-wood systems in the West, as has occured through the past three decades or so in Eastern Canada (McNally, 1978).

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UTILIZATION OF LODGEPOLE PINE FOREST AND FOREST PRODUCTS RESIDUALS FOR COMPOSITION BOARD

Thomas M. Maloney

ABSTRACT

Lodgepole pine (*Pinus contorta*) mill residues have been used in composition board manufacture for many years, usually in mixture with other species. Research has shown that lodgepole pine is an excellent species for many types of composition board such as hardboard, medium density fiberboard, underlayment grade particleboard, industrial grade particleboard, oriented strand board, flakeboard, and waferboard.

Large amounts of standing lodgepole pine killed by disease, insects, and fire are also available in the western United States and Canada. Some of this material can be used successfully to manufacture lumber and plywood, but most of it is unsuitable for such use. This lodgepole material, however, can be used effectively in manufacturing most types of composition board materials. An exception is waferboard where it is difficult to cut wide wafers from the relatively dry raw material (usually about 25% moisture content) without special pretreatments such as water soaking or steaming.

It may also be possible to produce composition lumber or components from lodgepole pine.

INTRODUCTION

Lodgepole pine (*Pinus contorta*) has proven to be an acceptable if not excellent material for various types of composition boards. It has been used in waferboard, industrial and underlayment particleboard (made mostly of planer shavings), hardboard, and medium density fiberboard. Even as standing dead trees, it has shown its suitability for composition board. As the composition board industry develops further, lodgepole pine is a logical raw material for use in the various products which are being manufactured now or which may be developed.

This paper will cover descriptive terminology for composition boards, the species characteristics of lodgepole pine which make it an excellent composition board raw material, the history of the use of lodgepole pine in the Inland Empire and British Columbia, and relatively recent research work further demonstrating the suitability of this species, including the useability of standing dead timber, for composition board.

DESCRIPTIVE TERMINOLOGY FOR COMPOSITION BOARDS

The general definition for these materials are presented in American Society for Testing and Materials (ASTM) "Standard Definition of Terms Relating to Wood-Base Fiber and Particle Panel Materials" as follows:

General Definitions

Wood-base fiber and particle panel materials: A generic term applied to a group of board materials manufactured from wood or other lignocellulosic fibers or particles to which binding agents and other materials may be added during manufacture to obtain or improve certain properties. Composed of two broad types, fibrous-felted and particleboards.

Fibrous-felted board: A felted wood-base panel material manufactured of refined or partly refined lignocellulosic fibers characterized by an integral bond produced by an inter-felting of fibers and, in the case of certain densities and control of conditions of manufacture, by ligneous bond, and to which other materials may have been added during manufacture to improve certain of its properties.

Particleboard: A generic term for a panel manufactured from lignocellulosic materials (usually wood), primarily in the form of discrete pieces or particles, as distinguished from fibers, combined with a synthetic resin or other suitable binder and bonded together under heat and pressure in a hot press by a process in which the entire interparticle bond is created by the added binder, and to which other materials may have been added during manufacture to improve certain properties. Particleboards are further defined by the method of pressing. When the pressure is applied in the direction perpendicular to the faces, as in a conventional multi-platen hot press, they are defined as flat-platen-pressed; and when the applied pressure is parallel to the faces, they are defined as extruded.

Wood-cement board: A panel material in which wood, usually in the form of excelsior, is bonded with inorganic cement.

Classification of Fibrous-Felted Boards

Structural insulating board: A generic term for a homogeneous panel made from lignocellulosic fibers (usually wood or cane) characterized by an intergral bond produced by interfelting of the fibers, to which other materials may have been added during manufacture to improve certain properties, but which has not been consolidated under heat and presure as a separate stage in manufacture, said board having a specific gravity of less than 0.50 but more than 0.16.

Hardboard: A generic term for a panel manufactured primarily from interfelted lignocellulosic fibers (usually wood), consolidated under heat and pressure in a hot press to a specific gravity of 0.50 or greater and to which other materials may have been added during manufacture to improve certain board properties.

Medium-density hardboard: A hardboard, as previously defined, in a density between 0.50 and 0.80 specific gravity.

High-density hardboard: A hardboard, as previously defined, with a specific gravity greater than 0.80.

Classification of Particleboards

Low-density particleboard: A particleboard, as previously defined, with a specific gravity less than 0.59.

Medium-density particleboard: A particleboard, as previously defined, with a specific gravity between 0.59 and 0.80.

High-density particleboard: A particleboard, as previously defined, with a specific gravity greater than 0.80.

As has been shown, particleboard is the generic term covering many types of board. This nomenclature has varied in North America. The major variance being to call waferboard and oriented strand board (OSB) by their own names. Waferboard is a product made with large flakes (usually over 1.5 by 1.5 in. in size) particularly for the board faces. Some waferboard is called "oriented waferboard" which means a product much like OSB OSB is made with slender flakes or strands (up to 76 mm in length) which has the strands in the face and core layers aligned. The face and core layers of OSB are aligned 90° to each other in a cross-ply fashion, the same as in plywood. OSB, currently, is made in either three- or five-layer construction.

A relatively recent product development is medium density fiberboard (MDF). As described in American National Standard ANSI A208.2-1980 "Medium Density Fiberboard for Interior Use," MFD is a dry-formed panel product manufactured from lignocellulosic fibers combined with a synthetic resin or other suitable binder.

The terms "composition board" or "composition materials" are used to cover all of the above described panel products.

SPECIES CHARACTERISTICS OF LODGEPOLE PINE

For the types of composition boards now produced, the species used are preferably those which:

1. Are lower in density.
2. Do not have growth characteristics such as wide, high-density latewood growth rings. This type of growth ring makes the compositon board products hard to machine.
3. Do not contain extraneous materials such as silica which also give machining problems.
4. Are relatively easy to convert to particles or fibers.
5. Tend to "plasticize" when being compressed in the hot press thus yielding panels with smooth surfaces.
6. Are easy to glue.

Lodgepole pine meets all of these criteria. Actual in plant production as well as laboratory research has shown that good, if not excellent products can be made with this species.

HISTORY OF USE IN THE INLAND EMPIRE AND BRITISH COLUMBIA

The first waferboard plant was built by the Pack River Lumber Company at Dover, Idaho (just outside Sandpoint, Idaho). This plant commenced operation in 1955 and lodgepole pine was one of the species used. The particleboard plants now or previously operating, producing underlayment and industrial (furniture and cabinet stock) boards in La Grande, Oregon; Missoula, Montana; Post Falls, Idaho, Grand Forks and Prince George, British Columbia, find lodgepole pine as part of their basic planer shaving furnish. Wet-process hardboard made in Pilot Rock, Oregon and MDF produced at Columbia Falls, Montana also finds lodgepole pine as part of the raw material. In fact, the wet-process plant uses dead lodgepole pine almost exclusively. At present, the plant is not quite running at full capacity, but it still uses 50,000 bone-dry units of lodgepole per year (2400 lbs or 1090 kg/unit).

The new Louisiana Pacific Corporation waferboard plant soon to commence operation in Chilco, Idaho is to run exclusively on green lodgepole pine. A new waferboard plant announced for the Okanogan Valley of British Columbia is to use the stagnant forests of lodgepole pine for raw material.

Personal discussions with plant representatives using lodgepole pine revealed that they were not finding any processing, gluing, or board property problems.

PAST RESEARCH

Work at the U.S. Forest Products Laboratory in Madison, Wisconsin has shown lodgepole pine to be a good flakeboard furnish. Extensive research at Washington State University in cooperation with the U.S. Forest Service investigated the use of dead standing lodgepole pine for composition board. Material from green trees was also used to manufacture control panels.

This extensive research was reported in the *Proceedings of the Tenth Washington State University International Symposium on Particleboard.* The reader is referred to this paper for details. In this research, particle geometries were varied by product according to typical industry practice. Tabulated on the following page are the particles used for the various products.

Conventional laboratory board-producing techniques were used for all boards but the phenolic-bonded hardboard. Hardboard of atmospherically ground fiber normally has the phenolic resin blended with the fiber as the raw material is ground into fiber in the attrition mill. The mill thus simultaneously serves as an attrition mill and blender. Since it was necessary to use fiber generated in an earlier phase of this research, the resin had to be added after fiber generation for the study of hardboard.

Board Type	**Particle Types and Amounts**
Underlayment	50% hammermilled particles (−6+42 Tyler screen size) [illegible] air-classified, ring-cut flakes [flakes over 0.020 in. (0.51 mm) in thickness removed]
Furniture Core (Three-Layer)	Furnish same as used for Underlayment Faces: 23% of the total for each face, −20 screen size particles Core: 54% of the total +20 screen size particles.
Door Core (Three-Layer)	Furnish same as used for Underlayment Faces: 15% of the total for each face, −20 screen size particles. Core: 70% of the total, +20 screen size particles.
Flakeboard (Three-Layer)	Faces: 20% of +9 drum-cut flakes for each face Core: 60% of a mixture of +9 and −9 drum-cut flakes (the larger flakes were used in the faces to enhance bending properties).
Hardboard	Pressure-refined fiber Atmospheric-refined fiber

It was found that the lodgepole pine from both living and dead trees could be converted successfully into a variety of composition board products. These included underlayment particleboard, furniture or industrial board, door core, hardboard, and medium-density fiberboard. As noted above, structural flakeboard (non-oriented) was also made and these had suitable properties. However wafer-type flakes could be produced only from the live trees, not from the dead standing trees. The dead standing material was about 25 % in moisture content and the flakes split into narrower widths than is found with conventional wafers.

Tables 1-4 present property data and response to high humidity exposure of boards made from dead standing lodgepole pine.

This research, plus plant experiences, shows that lodgepole pine is indeed, a good composition board furnish even as low-quality standing dead material. Thus, a large resource which is difficult to use in many typical forest products, stands ready for use in the composition board industry. The cost of harvesting the wood and transporting the finished product to market are the two economic factors that will govern the use of lodgepole pine in an expanded composition board market. The technical problems are essentially solved and optimization of processing or the development of new composition materials makes the use of this species even more viable.

At the present time, manufacturing costs for waferboard and oriented strand board are lower than for manufacturing sheathing-type plywood. This is due to the higher wood costs for plywood. Consequently, the new board plants being constructed close to the markets in the midwest, east, and south have a production cost advantage and a freight advantage for shipping their product to the major markets.

West coast board plants have the same freight cost disadvantage as for plywood. Thus, providing commodity-type panels in the lodgepole pine area does not seem to be appropriate now, except for west coast markets and export, unless some "value added" can be given the panels. Careful consideration of the market is needed before proceeding with production of the typical sheathing-type panels.

LUMBER OF LODGEPOLE PARTICLES

The author recently prepared a column for publication in *Plywood and Panel World* on the subject of composition board lumber. Part of this column which is in press follows:

> As we know, the "new" forest now being harvested is, for the most part, of lower quality than the old growth forests which supplied our needs until recently. The trees are smaller when harvested. Thus, there is a high level of low strength juvenile wood and considerable cross-grain formed around the knots. Lumber cut from these trees is of lower quality and is also prone to warp and twist. Warped and twisted lumber is difficult to use, causing much complaint in the field.
>
> Lumber manufactured from composition materials, however, has all of the raw material randomized throughout the particle mix which minimizes warp and twist. Most of the raw material coming into the plant can be used for the final product. Many sawmills have less than 50% yield from a log. A composition material lumber plant can be used for the final product. Many sawmills have less than 50% yield form a log. A composition material lumber plant may be able to achieve a yield up to 85%.
>
> Lumber is the most valued material in the forest products mix. A study a few years ago made a comparison of the relative value of lumber and its by-products. Lumber was given an index number of 100 as the highest value product. In comparison, pulp chips were 25, sawdust and planer shavings were 5, and hog fuel was 2.5. By producing lumber from these lower value materials (particularly the pulp chips), the resultant product would also have an index number of 100 – the most valued product. This is an economic goal well worth considering.
>
> The usual immediate reaction to the suggestion of composition material lumber is that it is not as strong as virtually all sawn lumber. True – but a wrong observation as to the way lumber is used.

Table 1.—Average Properties and Response to High Humidity of Underlayment, Furniture Core, and Door Core Boards of Dead Standing Lodgepole Pine

	Modulii of Rupture/Elasticity			**Internal Bond**		**Response to 90% Relative Humidity Exposure**			
Type of Board	**SG**	**MOR(psi)**	**MOE(psi x 10^6)**	**SG**	**PSI**	**LE(%)***	**MA(%)****	**TS(%)**	**MC(%)**
Underlayment	0.66	2490	0.415	0.65	144	0.43	11.9	14.2	20.7
		(17.2MPa)	(2861)		(0.99)				
Furniture Core	0.73	4150	0.580	0.73	169	0.44	11.5	11.0	19.9
		(28.6)	(3998)		(1.16)				
Door Core	0.47	1300	0.234	0.50	81	0.44	12.4	8.7	21.2
		(8.9)	(1613)		(0.56)				
	Grade								
ANSI A208.1***	IM1	1600	0.250		60	0.35	--	--	--
		(11.0)	(1723)		(0.41)				
	IM2	2100	0.325		60		--	--	--
		(14.5)	(2241)		(0.41)	0.35	--	--	--
	IM3	2400	0.400		80	0.35	--	--	--
		(16.5)	(2758)		(0.55)				
	ILI	800	0.150		20	0.30	--	--	--
		(5.5)	(1034)		(0.14)				

* LE: Linear expansion, MA: Moisture absorbed, TS: Thickness swell, MC: Moisture Content.

** Based on weight of specimens after conditioning at 50% RH.

*** American National Standard, ANSI A208.1-1979 "Mat-Formed Wood Particleboard."

Table 2.—Average Properties and Response to High Humidity Exposure of Flakeboard Produced from Dead Standing Lodgepole Pine

	MOR/MOE			**IB**		**Response to 90% Relative Humidity Exposure**			
	SG	**MOR(psi)**	**MOE(psi x 10^6)**	**SG**	**PSI**	**LE(%)***	**MA(%)****	**TS(%)**	**MC(%)**
	0.75	3480	0.580	0.77	67	0.20	13.6	20.3	21.3
		(24.0MPa)	(3998)		(0.46)				
	Grade								
ANSI 208.1***	2MF	3000	0.500		50	0.20			
		(20.7)	(3448)		(0.34)				

* LE: Linear expansion, MA: Moisture absorbed, TS: Thickness swell, MC: Moisture content.

** Based on weight of specimens after conditioning at 50% RH.

***American National Standard, ANSI A208.1-1979 "Mat-Formed Wood Particleboard."

Table 3.—Average Properties and Response to High Humidity Exposure of Hardboard Made from Atmospheric- and Pressure-Refined Fiber of Dead Standing Lodgepole Pine

		MOR/MOE			**IB**		**Response to 90% Relative Humidity Exposure**		
Process	**SG**	**MOR(psi)**	**MOE(psi x 10^6)**	**SG**	**PSI**	**LE(%)***	**MA(%)****	**TS(%)**	**MC(%)**
Atmospheric-Refined	0.94	6490 (44.7MPa)	0.489 (3371)	0.93	225 (1.55)	0.45	9.9	10.6	16.1
Pressure-Refined	1.01	10200 (70.3)	0.689 (4750)	1.01	290 (1.99)	0.39	9.5	10.5	15.4
PS 58-73*** Standard Board	0.50 or greater	5000 (34.5)	--	0.50 or greater	100 (0.69)	--	--	--	--

* LE: Linear expansion, MA: Moisture absorbed, TS: Thickness swell, MC: Moisture content.

** Based on weight of specimens after conditioning at 50% RH.

*** Voluntary Product Standard "Basic Hardboard." (PS 58-73)

Table 4.—Average Physical Properties of Medium Density Fiberboard of Dead Standing Lodgepole Pine Pressure Refined

		MOR/MOE		**IB**	
	SG	**MOR(psi)**	**MOE(psi x 10^6)**	**SG**	**PSI**
	0.72	4400 (30.3MPa)	0.400 (2757)	0.72	110 (0.76)
ANSI 208.2*	--	3000 (20.7)	0.300 (2068)	90	 (0.62)

* American National Standard, ANSI A208.2-1980. "Medium Density Fiberboard."

Wood is quite a variable material—a fact clearly understood by all those in the forest products industry. Clear wood specimens were used to determine the strength values shown in handbooks which in turn are the basis for establishing design levels. However, clear wood strength values cannot be used for the actual design values. Full size members with their inherent weaknesses are much lower in strength than the small clear wood specimens.

Until the relatively recent advent of machine type nondestructive testing, visual grading was the only way lumber was graded, even for uses calling for high stresses and loads. Even today most lumber is graded visually.

Thus, to be safe, allowable design values were established based on the weakest members in a particular grade. This means that most of the lumber far exceeds the design values required. Thus, most of a grade of lumber is "too good" for the job. This is a strong argument for nondestructive testing which measures the actual strength of each piece of lumber. Showing the actual strength enables proper engineering use of the material—but for the most part this is yet to be done.

The important point is that even high strength lumber is used according to relative low design values in structural use. For example, select structural Douglas fir lumber is one of the top grades of lumber. In the Western Wood Products Grading Rules, the design value for this lumber in tension is 1200 psi. This value must be multiplied by 2.1 (ASTM D 245 method for determining the allowable properties for visually graded material) to determine the minimum test strength of the lumber (2520 psi or 17.4 MPa) if it is to meet the grade. At Washington State University 113 specimens of nominal 2 by 4 in. by 8 ft. (51 by 102 mm by 2.44 m) select structural Douglas fir were recently tested in tension. The tension values ranged from 1280 to 10,250 psi (8.8 to 70.7 MPa), a tremendous range. The highest value was five times that required while the minimum value was only one-half of that required.

In another recent project, oriented composition material was made for lumber of COM-PLY® ("Fully Aligned Flakeboard Core for COM-PLY® Joists and Truss Lumber," research for the U.S. Forest Service headed by G. A. Koenigshof of the Southeastern Station in Athens, Georgia). All of the particles (1-1/2 in. or 40 mm maximum length) were oriented in the long direction of the board. This material had a low value of 3330 psi (23 MPa) and a high value of 3790 psi (26.1 MPa) in tension. The range of the tension property was quite narrow (3330 to 3790 psi) as compared to the sawn lumber (1280 to 10,250 psi). A great advantage of composition materials is the ability to control the range of a property by producing relatively uniform material (this was discussed in detail in "Board Talk," *Plywood and Panel World*, June 1983). All composition material lumber tested exceeded the minimum required strength for Douglas fir select structural lumber.

As many critics would point out, most of the select structural lumber was indeed stronger than the composition material lumber. But the important fact, from a structural standpoint, is that there were some pieces of lumber that were below minimum requirements. The composition material lumber, however, met the specification for tension which covers most structural uses of the lumber. The point is that the composition material lumber was adequate for the applications – and these applications cover most uses of this grade of lumber. This is not an example showing a small specialty use of composition material lumber. It shows that the use of such lumber is possible in most of the conventional structural applications which is an enormous market. It is a market which, like the composition material panel market, can possibly be served by using lower quality species near the urban markets.

Composition materials lumber is close to being developed. Most of the technology exists. It is now a matter of establishing the correct production parameters for a given raw material, ensuring that all appropriate strength requirements are met, developing materials with appropriate nail and truss plate holding power, and ensuring that dimensional changes caused by exposure to water are not excessive.

Lodgepole pine should also work well for lumber. However, economics will govern whether such lumber can be made on the west coast. Shipping costs to the east may be prohibitive. More importantly, similar material could be made in the east from that area's low quality forest. The west coast material would then have to have some unique advantages or better quality which it well could have because lodgepole pine probably would be a better species to use than the hardwood species readily available for utilization in the east.

Such new materials may fit into the export market. It may also be possible to develop "value added" products such as building components using composition board technology.

CONCLUSION

Lodgepole pine is a good species for use in composition materials. The economics of production, transporting, and marketing as well as man's ingenuity in improving the processing and use of the products particularly in value-added materials, will determine this species' future in the rapidly expanding composition board industry. The key to future success will be in developing value-added products, such as engineered structural components, using the composition boards. Expanded markets probably lie overseas because of the greater land shipping costs now as compared to the past.

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UPGRADING LODGEPOLE PINE LUMBER BY NONDESTRUCTIVE TESTING

Roy F. Pellerin

ABSTRACT

Machine stress rating (MSR) is now well accepted for grading structural dimension lumber. Being that the MSR method establishes the grade based on the properties of the individual piece of lumber, the concept is species independent.

MSR is best known for its application to species such as Douglas-fir and hemlock that have been well established for structural application. However, MSR grading of white woods is also successfully being done. The decision of whether to use MSR depends upon economics and the quality of wood that is being graded, regardless of species.

INTRODUCTION

This paper reviews research on the potential yield from MSR of lodgepole pine dimension lumber. The results indicate an adequate yield of structural grade lumber for MSR to be profitable.

Lodgepole pine, like many species, can be upgraded for use in engineered structures through machine stress rating (MSR). This means more value and a larger market for lodgepole pine dimension lumber.

With an opening statement like that, I should be able to end my presentation here and field questions for the remainder of my allotted time. However, since undoubtedly you have been caught off-guard, I have anticipated some of your questions. These anticipated questions will be answered in a sequence which will give some meaningful structure to this question and answer session.

QUESTION: the first obvious question is – what is MSR?

ANSWER: MSR is the sorting of dimension lumber by a machine which measures the modulus of elasticity (E) of the individual piece. MSR, together with a visual override for edge knots, establishes the grade of the piece.

The philosophy of MSR is best described in Figure 1, where the data points represent a typical scatter plot of the relationship which exists between E and the strength of lumber. The regression line is the line that represents the best relationship for the data between E and strength. The vertical spread of the data at a given E value shows the variability that exists.

It has been shown through research, that the data points along the lower part of the scatter plot represent the lumber which is most likely to possess edge knots, therefore justifying the visual override for edge knots.

QUESTION: What grades are available through MSR?

ANSWER: Table 1 lists the E categories and corresponding strength values for MSR-graded lumber.

Table 1. – Categories of MSR Lumber

Modulus of elasticity E x10^{b}pbi	Extreme fiber in bending F_b psi	Tension parallel to grain F_t psi	Compression parallel to grain F_c psi
1.0	900	350	725
1.2	1200	600	950
1.3	1350	750	1100
1.3	1450	800	1150
1.3	1650	1020	1320
1.4	1500	900	1200
1.5	1650	1020	1320
1.6	1800	1175	1450
1.7	1950	1375	1550
1.8	2100	1575	1700
1.9	2250	1750	1800
2.0	2400	1925	1925
2.1	2550	2050	2050
2.2	2700	2150	2150

QUESTION: How do the E values of visually-graded lumber compare to the E values of MSR lumber?

ANSWER: Figure 2 illustrates that visual grading in two different mills can result in different stiffness distributions with the same species. By contrast, the MSR grades are restricted more in E distribution by the grading machine function. Figure 3 illustrates the E distribution data reported for two grades from one mill.

QUESTION: How do the strength values of visually-graded lumber compare to the strength values of MSR lumber?

ANSWER: Figure 4 shows accumulative distribution function for four visual grades and two MSR categories of hem-fir lumber.

Figure 5 illustrates the advantage in tensile load carrying capacity afforded to the user of MSR lumber over visually-graded lumber.

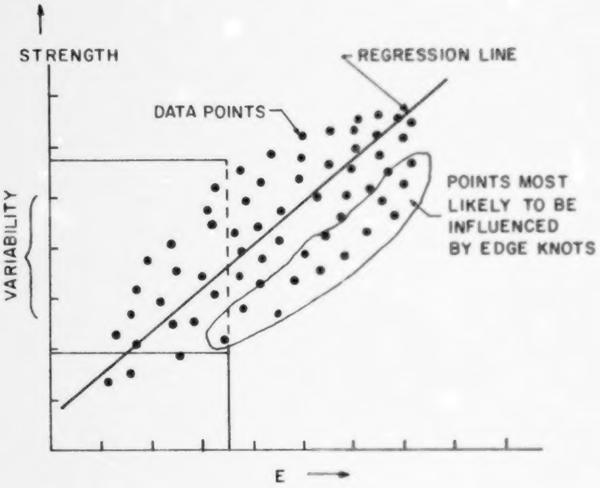

Figure 1. – Predicting strength by using a measurement of modulus of elasticity (E) and a visual override for edge knots.

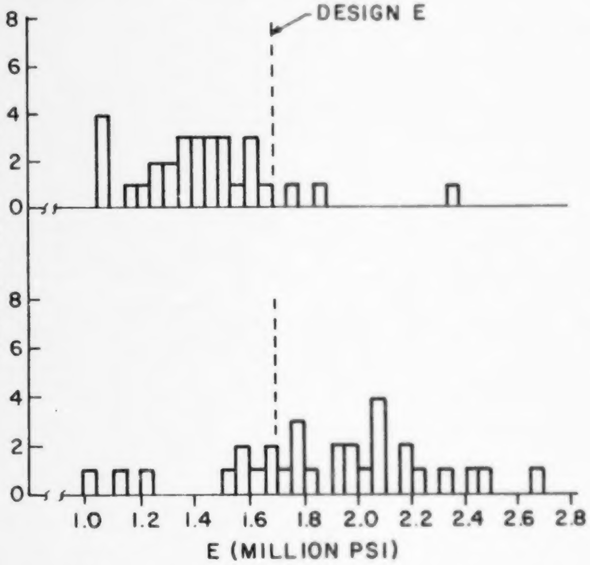

Figure 2. – An example of the difference in E in samples of the same grade of lumber taken from two lumber mills. USDA Forest Service General Technical Report FPL 7.

QUESTION: What kind of yields of MSR categories can be expected from mill-run lumber?

ANSWER: Figure 6 illustrates the typical percentage yield for mill run lumber which has been graded both visually and by MSR.

Figure 7 shows accumulative distribution functions for 1,077 pieces of 2 by 4 in. fir-larch and for 1,032 pieces of 2 by 4 in. SPF lumber.

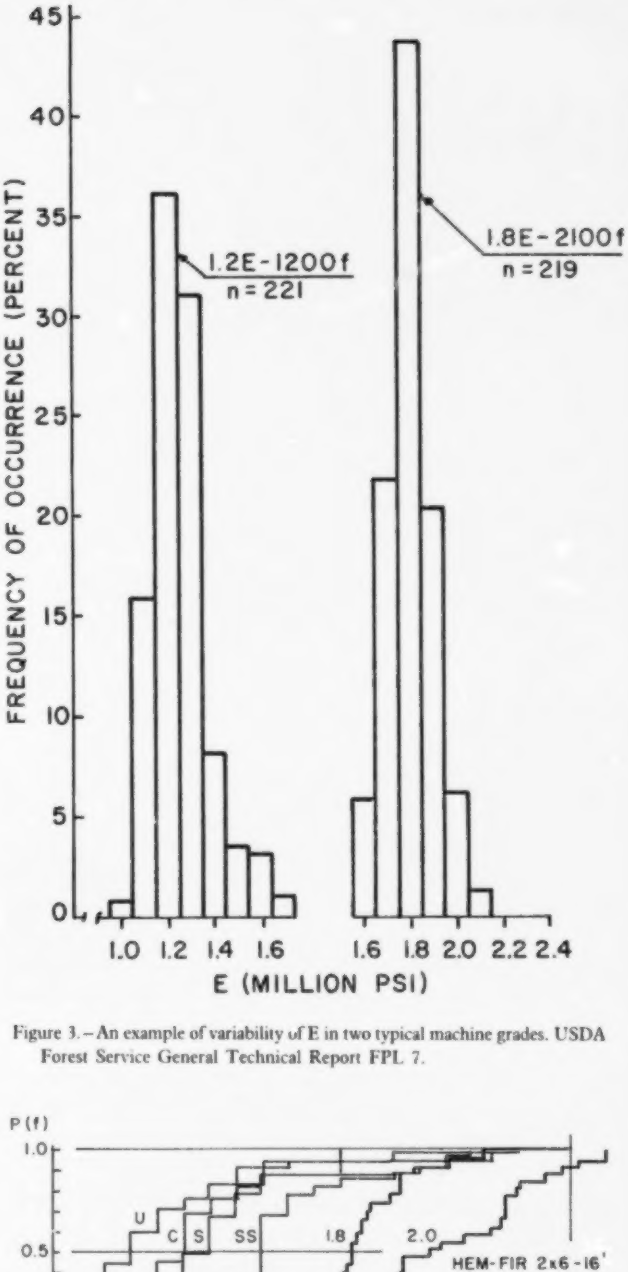

Figure 3. – An example of variability of E in two typical machine grades. USDA Forest Service General Technical Report FPL 7.

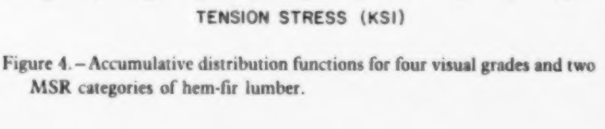

Figure 4. – Accumulative distribution functions for four visual grades and two MSR categories of hem-fir lumber.

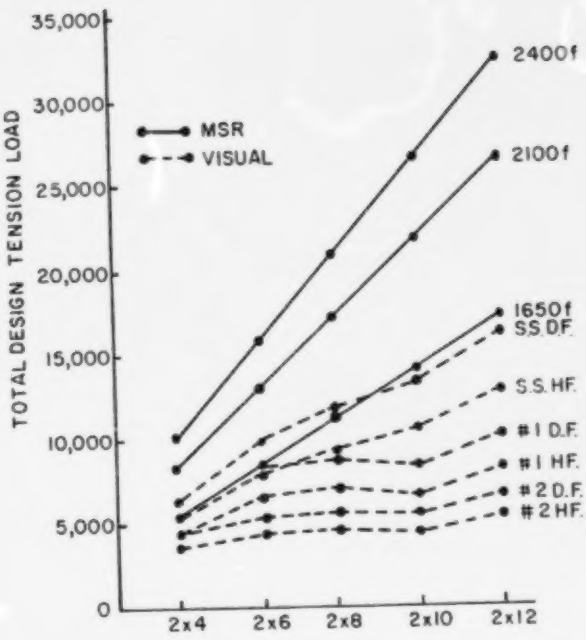

Figure 5.—Total design tension loads for various grades and sizes of lumber.

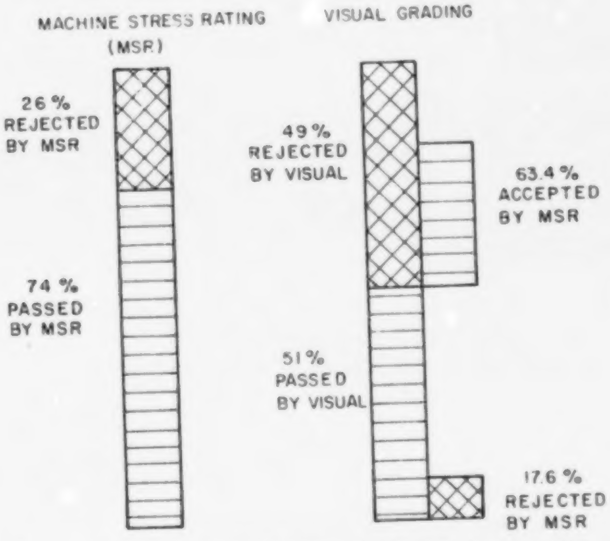

Figure 6.—Comparable yields of lumber graded by both visual and MSR.

QUESTION: What machines are available for MSR?

ANSWER: Several machines are available for MSR, but only one is used predominantly in North America and that is the CLT-1.

QUESTION: What is a typical installation cost for the CLT-1?

ANSWER: $250,000

$153,221	CLT
11,855	Bending Proof Loader
3,185	Pelster Testing
2,000	Spare Parts
2,000	Shipping
3,000	Start Up
20-50,000	Installation

QUESTION: At that price, how can a mill afford to install a CLT-1?

ANSWERS: Tables 2, 3, and 4 illustrate a conservative figure for the increased value of lumber graded with MSR. Some of the larger mills have paid off the installation costs within six months after which the increase value goes into PROFIT. Some machines which were installed as early as 1963 are continuing to return this same kind of value.

Table 2.—1979 average prices for visual grades of a typical mix.

Grade	Mix M Bd. Ft.	$/M	Value
Select Structural	60	278	$ 16,680
Std. & Better	770	244	187,800
Utility	130	160	20,800
Economy	40	75	3,000
Total	1000		$228,360

Table 3.—1979 average prices for MSR and visual grades.

Grade	Mix M Bd. Ft.	$/M	Value
2400F-2.0E	20	385	$ 7,700
2100F-1.8E	30	365	10,950
1650F-1.5E	190	310	58,900
Std. & Better	590	244	143,960
Utility	130	160	20,800
Economy	40	75	3,000
Total	1000		$245,310

Table 4.—Increased value with MSR

$245,310
−228,360
or $16.95
or $16.95 per m Bd. Ft. on total production.

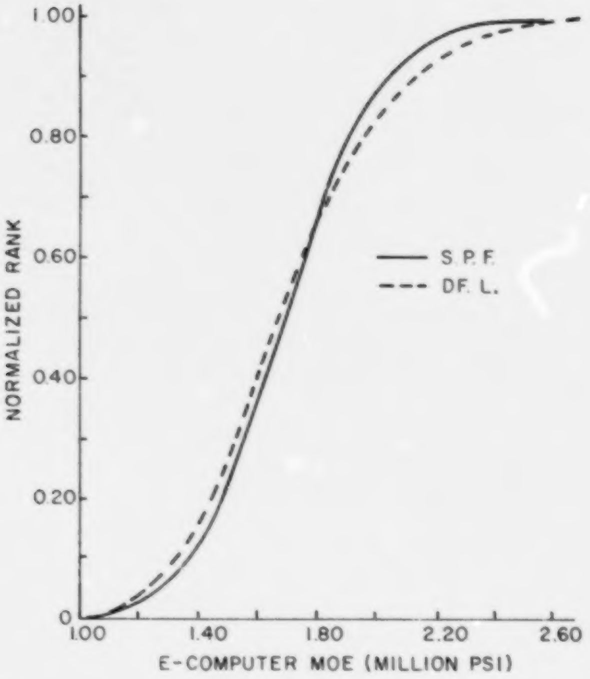

Figure 7.—Accumulative distribution functions for 1,077 pieces of 2 x 4 in. fir-larch and for 1,032 pieces of 2 x 4 in. SPF lumber.

In order to focus more on lodgepole pine, I made a telephone survey of mills currently producing MSR lodgepole pine lumber. The survey questions and the answers received are as follows:

1. Has MSR made lodgepole pine dimension more marketable?
    a) In all cases the answer was a strong yes.
    b) Where the visually-graded market was limited primarily to Texas, the MSR market has expanded to Seattle, the Great Lakes, Kansas, etc.
    c) As one producer put it, "MSR has moved lodgepole pine from a "Dog" of a species to a valuable and marketable product."
2. What is the primary end-use of MSR lodgepole pine?
    a) Engineered structures, but primarily trusses.
3. What kind of increased value are the mills receiving for MSR lodgepole pine?
    a) Some grades are bringing a premium of as much as $50/mbf.
    b) The important thing to the producers of MSR lumber was that during the slowdown of the wood industry—MSR lumber was still moving.
4. Is there an export market for MSR lodgepole pine other than the U.S./Canada?
    a) One producer reported exports to Australia.
    b) The United Kingdom has approved SPF from Canada. This market could be significant since the U.K. imports approximately 95% of the lumber they use.

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UTILIZATION OF LODGEPOLE PINE IN PULPING

John V. Hatton and K. Hunt

ABSTRACT

Lodgepole pine is now widely accepted as a pulp furnish in contrast to its "weed species" designation of two decades ago. This was confirmed by a mill survey conducted in 1983 in the western United States and Canada aimed at quantifying the amounts of sound and beetle-killed lodgepole pine used, the pulping processes applied and the variety of end products for which these pulps are used.

Seventy-two questionnaires were distributed to all mills in five states and two provinces. Of these, 61 mills responded; 26 were using some percentage of lodgepole pine in their pulping operations, including 23 which use some (amount generally unknown) percentage of mountain pine beetle-killed material.

Nineteen of the responding mills use lodgepole pine to make kraft pulps, six make refiner mechanical or thermomechanical pulps and one makes defibrated wood for a range of fibreboard products. Kraft and mechanical pulps from lodgepole pine are used for a wide variety of end products including fine papers, communications, packaging, tissue and newsprint grades.

INTRODUCTION

Lodgepole pine (*Pinus contorta* Dougl.) occurs in the western United States and Canada on a wide variety of sites and principally in the Rocky Mountains. Although found in pure stands as well as in association with other species, it has historically been considered a "weed" tree among western softwoods (Benson, 1973) partly because of certain economic and technical problems associated with the manufacture of solid products from lodgepole pine.

For pulp, paper and board production, however, there is ample evidence to suggest that lodgepole pine should be a desirable species based on its fibre morphology and wood chemistry (Isenberg, 1980). This conclusion is supported by many laboratory studies using a variety of pulping processes.

Sound lodgepole pine cooks well by the kraft (Baranyay, 1973; Hatton, 1972; Hatton, 1975; Hatton, 1976; Horn, 1972; Hunt, 1978; Johnstone, 1973; Lowery, 1977; MacLeod, 1984; Martin, 1949; McGovern, 1951), polysulphide (Green, 1975) and kraft-AQ (MacLeod, 1982) processes to give bleachable-grade pulps with yields ranging from 44.0% (Martin, 1949) to 47.0% (MacLeod, 1984), od wood, at 30 Kappa number. These pulps can be bleached easily to high brightnesses and have mechanical properties equivalent to other western softwoods with similar morphology (MacLeod, 1982). The kraft pulping of tree components (Johnstone, 1973), hydroelectric wood (Hatton, 1976), whole-tree chips (Hatton, 1975) and chips from unbarked boles (Horn, 1972) has also been investigated. Prolonged outside storage of lodgepole pine chips reduced both the yield and mechanical properties of kraft pulps (Hatton, 1972).

Lodgepole pine cooks easily by the sulphite process (McGovern, 1951) to give easily-bleachable pulps which, however, could give rise too pitch problems in papermaking. Acid bisulphite pulping of lodgepole pine heartwood (Rickey, 1974) was easier than that of other pine heartwoods but the pulping rate was slightly inhibited by the presence of stilbenes. However, as shown later, very little pine heartwood is used in any of the major pulping processes.

Lodgepole pine gives stone groundwood pulps with good brightnesses and mechanical properties and at low energy consumption (McGovern, 1951), and is used commercially in admixture with other softwoods to give refiner mechanical and thermomechanical pulps of good opacity and strength (Hanson, 1978).

The principal concern with utilization of lodgepole pine for solid products or for pulp and paper is the effect of mountain pine beetle-killed material on processing and product quality. The extent of the devastation wrought by the mountain pine beetle on the lodgepole pine resource has been described several times earlier in this Symposium and will not be repeated here. The key questions which relate to the use of beetle-killed lodgepole pine in pulping include the following: How long can a tree be left on the stump after beetle attack before its quality deteriorates to a level beyond which it cannot be used in pulping? Is one or more of the major pulping processes more tolerant to the effects of reduced wood quality than other processes? If so, which, and what are these differences expressed quantitatively? What are the effects of site, secondary stem insect activity and microorganism type and population on the rate of deterioration of killed trees? Do chemical or mechanical pulps from beetle-killed wood behave differently to corresponding pulps from sound wood either on the pulp machine, in papermaking or in the pressroom? In short, much more research needs to be done to broaden our understanding of the interrelationships between length of time since tree death, insect activity and microorganisms, and pulp yield, quality and papermaking properties if we are to effectively use the increasing quantities of dead lodgepole pine currently available.

Few studies are available on the effects of using dead lodgepole pine in pulping. In chipping, the quantities of pin chips and fines increase with deteriorating tree quality (Dobie, 1978; Lowery, 1977) and more power is required than for sound wood (Lowery, 1977).

Laboratory data from the kraft pulping of dead lodgepole pine are contradictory. One study (Lowery, 1977) reports no significant differences between the pulping of sound and dead wood, but a second (McGovern, 1951) reports losses in pulp yield and quality, slower cooking, increased rejects and increased alkali consumption for dead relative to sound wood. Sulphite pulping of sound and dead lodgepole pine gave equivalent results (McGovern, 1951) but stone groundwood pulps from dead wood were darker and weaker than those from sound wood.

Distribution and Harvest

In 1973 the mature volume of lodgepole pine in British Columbia was 1.121 billion m^3 accounting for 14.2% of the total mature volume of softwoods in that province (BCFS, 1975). The corresponding distribution of net volumes of merchantable lodgepole pine in the western United States (USDA, 1977) is shown in table 1. The total growing stock in the United States, 0.747 billion m^3, is less than that in British Columbia and accounts for only 10.1% of the total softwood growing stock. Tree diameters of other western softwoods are larger than those of lodgepole pine such that sawtimber from these species constitutes 82% of their growing stock. The corresponding value for lodgepole pine is 45.0% (table 1).

Harvesting data for lodgepole pine are not available for the western United States, but they are available for British Columbia. It is interesting to note the dramatic increase in lodgepole pine harvested for lumber and pulp and paper over the period from 1960 to 1982 relative to the total softwood cut. Figure 1 shows that the total softwood harvest in British Columbia rose from 33.4 million m^3 in 1960 to a high of 76.2 million m^3 in 1979, followed by a disastrous drop to 44.6 million m^3 in 1982. [Incidentally, the trend line from 1970 to 1982 closely resembles that for the consumption of pulpwood and residue in Canada (fig. 2)]. Over the 19-year period from 1960 to 1979 lodgepole pine harvest rose from 1.3 million to 14.8 million m^3 before dropping to 10.3 million m^3 in 1982 (fig. 3). During the period 1960 to 1982 the cut of lodgepole pine, in relation to total softwood harvest, increased consistently from 3.8% in 1960 to 23.1% in 1982 (fig. 3) in spite of the large fluctuations indicated in figure 1. This remarkable growth of lodgepole pine confirms its graduation from a "weed" to a commercially valuable softwood resource for use in lumber and other solid wood products. How significant, however, is it as a pulpwood furnish?

To place the current utilization of lodgepole pine as a pulp furnish in proper perspective a brief questionnaire was distributed in 1983 to all pulp mills in western Canada and the United States requesting selected information on the processing of sound and bark beetle-killed lodgepole pine for pulp, paper and board products (Appendix I).

ANALYSIS OF MILL SURVEY

Twenty-five of 26 mills in Alberta and British Columbia and 36 of 46 mills in California, Idaho, Montana, Oregon and Washington participated in this survey for a net response of 85%. The distribution of participating mills and those mills using lodgepole pine is shown in figure 4. There was no reported use of lodgepole pine for pulp, paper or board by mills in California.

Table 1.—Net volumes of merchantable lodgepole pine in the western United States.

	Sawtimber			Growing stock			
State	Million m^3	% all species	% all softwoods	Million m^3	% all species	% all softwoods	Sawtimber, % of growing stock
Oregon	50.82	2.5	2.6	115.78	5.1	5.5	43.9
Washington	19.18	1.2	1.3	43.95	2.4	2.7	43.6
California	19.56	1.6	1.6	24.64	1.8	1.9	79.4
Idaho	51.90	7.9	7.9	113.27	12.6	12.6	45.8
Montana	95.20	20.7	21.0	257.86	32.6	32.9	36.9
Wyoming	45.72	35.8	36.3	79.39	39.0	40.3	57.6
Colorado	41.52	16.0	17.4	86.87	20.4	24.3	47.8
Nevada	0.48	7.4	7.5	0.58	7.8	8.2	82.8
Utah	11.72	15.9	17.3	24.34	19.4	24.1	48.2
	336.10	5.2	5.4	746.68	9.4	10.1	45.0

[1] Not including Alaska, where lodgepole pine growing stock is only 0.1% that of all species

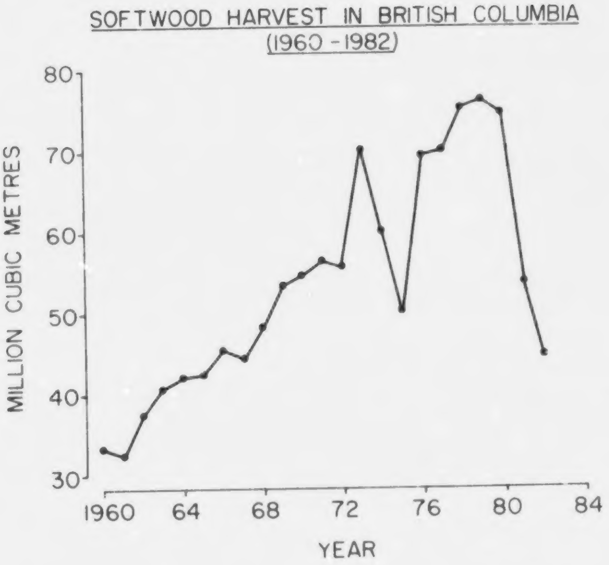
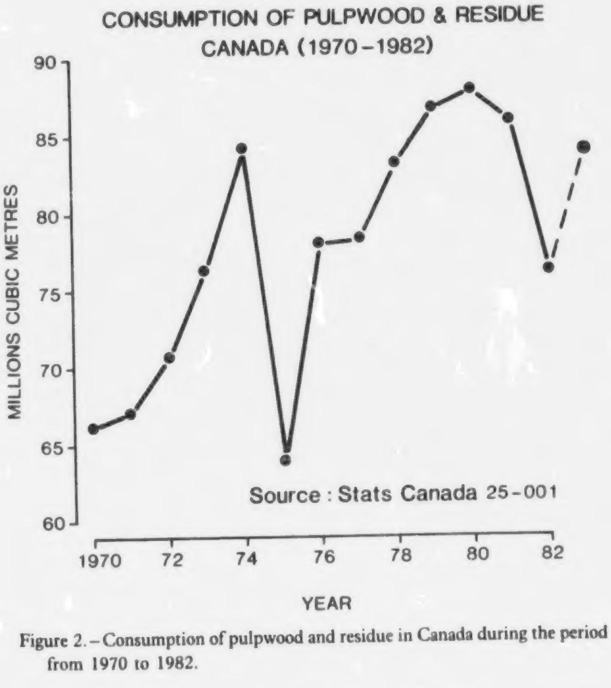


Figure 1. – Total softwood harvest in British Columbia during the period from 1960 to 1982.



Source : Stats Canada 25-001

Figure 2. – Consumption of pulpwood and residue in Canada during the period from 1970 to 1982.

Pulping of Lodgepole Pine – Location and Process

The distribution of those mills surveyed, responding and using lodgepole pine is shown in table 2 by province/state and for each of the major pulping processes. Mechanical pulp mills surveyed were using one or more of the stone groundwood

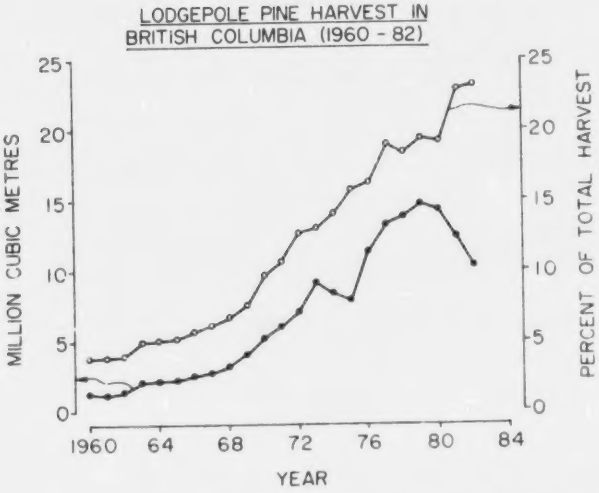


Figure 3. – The cut of lodgepole pine in British Columbia increased from 3.8% to 23.1% of the total softwood harvest during the period from 1960 to 1982.

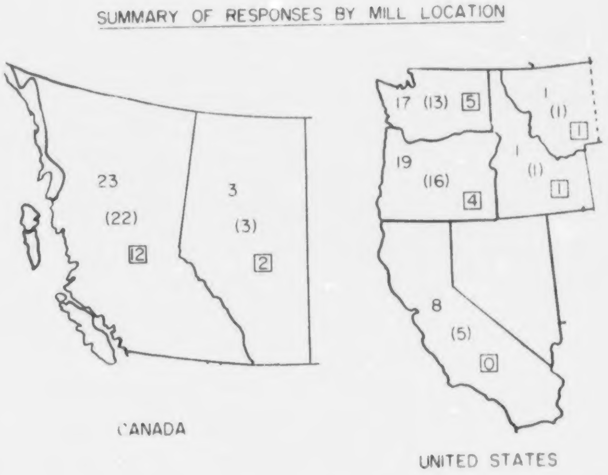


Figure 4. – Summary of responses, showing the numbers of mills surveyed (largest number for each of the seven regions), those responding (in parentheses) and those using lodgepole pine (in boxes).

(SGW), refiner mechanical (RMP), thermomechanical (TMP) and chemithermomechanical (CTMP) pulping processes. Other processes included sulphite (S), neutral sulphite semi-chemical (NSSC) and defibrated wood (DW).

The number of mills surveyed by process totalled 30 and 51 for Canada and the United States, respectively. These numbers are greater than those shown in figure 4 because four Canadian and five United States mills are using more than one pulping process as defined in table 2. Of these combined 81 mills, 39 are kraft mills, 15 are mechanical pulp mills and 27 are using a variety of other pulping processes.

Table 2.—Summary of mill responses by location and major pulping process.

	Kraft			Mechanical[1]			Other[2]		
	Mills surveyed	Mills replied	Mills using lodgepole pine	Mills surveyed	Mills replied	Mills using lodgepole pine	Mills surveyed	Mills replied	Mills using lodgepole pine
Canada									
Alberta	2	2	2	--	--	--	1	1	0
British Columbia	18	17	11	6	5	2	3	1	0
United States									
California	4	4	0	1	0	--	4	1	0
Idaho	1	1	1	--	--	--	--	--	--
Montana	1	1	1	--	--	--	--	--	--
Oregon	7	7	2	4	4	1	11	8	1
Washington	6	5	2	4	4	3	8	5	0

[1] Including stone groundwood, refiner mechanical, thermomechanical and chemi-thermomechanical pulping.

[2] Including sulphite, neutral sulphite semichemical and defibrated wood pulping.

Kraft Pulping Process

Of the 20 Canadian and 19 United States kraft pulp mills surveyed, 19 and 18, respectively, responded. More Canadian mills (13) than United States mills (6) are using lodgepole pine in their multi-species wood furnish.

Mechanical Pulping Processes

Of the six Canadian and nine United States mechanical pulp mills surveyed, five and eight, respectively, responded. In contrast to kraft processing, more United States mills (4) than Canadian mills (2) are using lodgepole pine as a component of their wood furnish.

Other Pulping Processes

Of the two Canadian and 14 United States mills responding, only one of the latter is using lodgepole pine—and that to manufacture defibrated wood pulp.

Accordingly, the remainder of this discussion will focus on the net 13 kraft and two mechanical pulp mills in Canada and the six kraft, four mechanical and one defibrated wood pulp mill in the United States, all of which use lodgepole pine (fig. 5).

Quantity and Quality of Lodgepole Pine Used in Pulping

The degree to which lodgepole pine is used in pulping is shown in tables 3 and 4 for Canadian and United States mills, respectively.

In western Canada, lodgepole pine constitutes a significant portion of the chip furnish in both kraft and mechanical pulping, ranging from a low of 13 to a high of 60%. The corresponding use in western United States mills is generally lower for both of these processes and ranges from a low of one to a high of 50%. Mill no. 139 is an exception in that it uses 90% of lodgepole pine in the form of whole-tree chips.

Based on the 1982 pulp production tonnages of the 25 mills using lodgepole pine in chemical and mechanical pulping, the percentages shown in column 4 of tables 3 and 4 can be alternatively stated as follows. In western Canada 13 mills produced kraft pulp containing 32.3% lodgepole pine. Similarly, 2 mills produced mechanical pulp containing 29.7% lodgepole pine. The corresponding values for six kraft mills and four mechanical pulp mills in the western United States were 14.5%

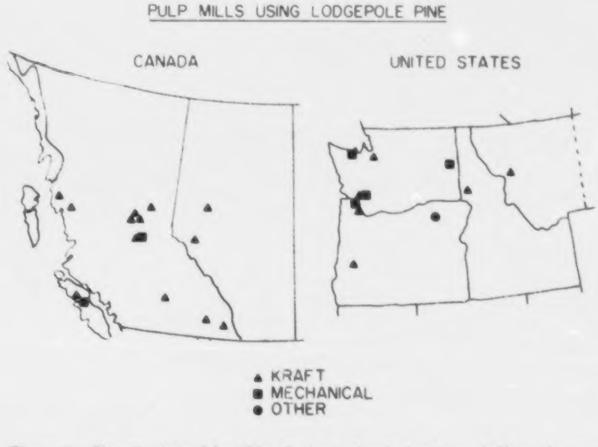


Figure 5.—Distribution of the 19 kraft, six mechanical and one defibrated wood pulp mill which used lodgepole pine in their operations in 1982.

and 31.3%, respectively, for a 25-mill combined value of 26%.

Table 3.—Quantity and quality of lodgepole pine used for pulping in western Canada.

Mill no.	Process	Bleached	% by weight of lodgepole pine in furnish	Relative % of roundwood to chips in furnish (R:C)	Amount of beetle-killed lodgepole pine in furnish
201	K	✓ + U[1]	53	0:100	33
202	K	✓	25	0:100	25
203	K	✓	13	0:100	✓[2]
206	K	✓	60	65:35	X[3]
207	K	✓	50	30:70	X
209	K	✓	25	0:100	✓
211	K	✓	16	NK[4]	✓
215	K	✓	15	0:100	5
216	K	U	55	0:100	✓
217	K	✓	45	3:97	6 to 9
224	K	✓ + U	45	0:100	✓
225	K	✓ + U	45	0:100	✓
226	K	✓	15	NK	✓
203	TMP	✓	32[5]	0:100	✓
227	TMP/CTMP	✓	25	0:100	10

[1] U = unbleached; [2] Actual amount not known; [3] X = none used;

[4] NK = not known; [5] None used in 1983

Table 4.—Quantity and quality of lodgepole pine used for pulping in western United States.

Mill no.	Process	Bleached	% by weight of lodgepole pine in furnish	Relative % of roundwood to chips in furnish (R:C)	Amount of beetle-killed lodgepole pine in furnish
106	K	✓	1	0:100	✓[1]
107	K	✓ + U[2]	30 to 50	0:100	✓
117	K	U	7	20:80	30
118	K	✓	10	0:100	✓
127	K	✓ + U	12	46:54	62
135	K	U	1	0:100	✓
113	RMP	✓	3	0:100	✓
128	TMP	✓	50	50:50	50
130	RMP	U	5	0:100	X[3]
131	RMP/TMP	✓	20 to 30	0:100	75
139	DW	U	90	0:100[4]	100

[1] Actual amount not known; [2] U = unbleached; [3] X = none used;

[4] Whole-tree chips.

Chip Sources

The increasingly significant role of lodgepole pine as a pulpwood furnish is due principally to the ready availability of residual chips from sawmilling operations. This is confirmed by the data in tables 3 and 4 which show that, of the 13 Canadian and 10 United States kraft and mechanical pulp mills which quantified the ratio of roundwood to sawmill residual chips in their furnishes, 10 Canadian and seven United States mills are using sawmill residual chips exclusively. The largest roundwood:chip ratio noted, 65:35, was for Canadian mill no. 206.

Chip Quality

Twenty-two of 25 responding mills are using beetle-killed lodgepole pine in their chip furnish, but the majority were unable to be quantitative. This lack of firm data is not surprising because of the large amounts of purchased chips used and the impossibility of distinguishing sound from beetle-killed material when in chip form. We conclude, therefore, that the percentages quoted in the last column of tables 3 and 4 are generally no more than best estimates.

End Uses of Lodgepole Pine Pulps

Lodgepole pine pulps are used in a wide range of end products categorized as shown in tables 5 and 6 for western Canada and the western United States, respectively. The principal end products made from western Canadian pulps are used for communications, fine paper, newsprint, packaging and tissue grades, whilst western United States pulps are used predominantly for linerboard, newsprint, packaging and paperboard grades. These end uses are fully representative of those found for other bleached and unbleached softwood kraft and mechanical pulps produced in those regions of Canada and the United States surveyed.

Table 5.—End uses of lodgepole pine pulps in western Canada

Mill no.	Process	End Products[1]
201	K	B, D
202	K	D, O
203	K	C, I, J, K, L
206	K	D, L
207	K	B, D, H, O
209	K	B, D, H, K, L, O
211	K	B, D, L
215	K	A, B, D, K, L, N, O
216	K	I, L
217	K	B, D, L, O
224	K	B, D, H, K, L
225	K	D, D, H, L
226	K	B, D, O
203	TMP	K
227	TMP/CTMP	D, K, O

[1] A = base papers; B = communications;
C = corrugating medium; D = fine papers;
E = groundwood specialties; F = hardboard;
G = insulation board; H = kraft specialties;
I = linerboard; J = market pulp; K = newsprint;
L = packaging; M = paperboard;
N = photographic papers; O = tissue.

Table 6.—End uses of lodgepole pine pulps in western United States.

Mill no.	Process	End Products[1]
106	K	M
107	K	L
117	K	I
118	K	D
127	K	I, L, M
135	K	I, L
113	RMP	K
128	TMP	K
130	RMP	K
131	RMP/TMP	E, K
139	DW	F, G

[1] Letters have same meaning as in table 5.

SUMMARY

Lodgepole pine has gained increasing acceptance as a pulpwood furnish in the last two decades and is now a commercially valuable fibre resource. It enters a mill primarily in the form of sawmill residual chips, and is used extensively with other species in the manufacture of unbleached and bleached kraft and mechanical pulps used to make a wide variety of end products.

It is anticipated that the use of lodgepole pine in pulping will increase from 1982 levels as efforts are intensified to learn how best to process beetle-killed lodgepole pine in particular.

ACKNOWLEDGEMENTS

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APPENDIX I

Questionnaire on Lodgepole Pine Usage mailed to all pulp mills in western Canada and western United States, June 21, 1983, and sent again to non-respondents September 16, 1983.

1. Does your mill currently process lodgepole pine for pulp?
2. If so, what was its percentage by weight of the total wood furnish to the mill in 1982?
3. What were the relative percentages of lodgepole pine roundwood and residual chips used in your mill in 1982? (e.g. 30:70).
4. What percentage (if known) of the total lodgepole pine used in your mill in 1982 was infected or killed by the mountain pine beetle? If not known quantitatively, was *any* mountain pine beetle-killed wood used in your mill in 1982?
5. What pulping process(es) was (were) used in your mill in 1982 to process lodgepole pine?
6. Was the pulp bleached or unbleached?
7. What end products was (were) your lodgepole pine pulp(s) used for in 1982? (e.g. Fine papers, Newsprint, Communications, Packaging, Tissue, Other).

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UTILIZING LODGEPOLE PINE FORESTS OF THE 21ST CENTURY—A RESEARCH PROGRAM

Peter Koch

ABSTRACT

Process invention and application are the end products of research scheduled to fill the technological needs. Routes to achieving such invention vary with investigator. One route that has proven successful—and is contemplated here—calls for a step-wise procedure comprised of the following components, listed in sequence of accomplishment. Work to date is on schedule and within budget.

1982-1992 Search the lodgepole pine literature, and process literature applicable to lodgepole pine; digest this information.

1982-1984 From survey data, arrange to have the North American lodgepole pine resource tabulated and graphed by county (or survey unit). 1983-1984 Identify a few representative lodgepole pine acreages in the United States for which responsible land managers seek intensified utilization.

1983-1984 Systematically sample the North American population of lodgepole pine (variety *latifolia*, and less intensively, *murrayanna*).

1985-1987 Characterize the representative acreages identified and publish an atlas depicting and describing these acreages in such a manner that new processes can be designed specifically for them.

1985-1990 From the systematic sample of trees, characterize wood, bark, foliage, and roots of lodgepole pine as industrial raw materials.

1983-1991 Invent new processes and incorporate known processes into new manufacturing systems that should be profitable; make economic analyses of these systems; demonstrate the most promising.

1990-1992 Write a U.S. Department of Agriculture Handbook summarizing pertinent data on: the resource (with background data on physiology and silvics); characterization of representative acreages; characterization of wood, bark, foliage, and roots; and processes by which lodgepole pine is converted to products, and their economic feasibility.

The needed processes should be moderate in capital, labor, water, and energy requirements, should accept trees of all diameter classes, and should yield high-value commodity products, with a high percentage of the complete tree (above- and below-ground biomass) ending as salable product.

INTRODUCTION

Lodgepole pine occupies about 5¼ billion ha (13 million acres) of commercial forest land in the United States (containing 722 million m^3 or 25.5 billion cubic feet of lodgepole growing stock and over 65 billion board feet of lodgepole timber, mostly in Montana, Idaho, Wyoming, Colorado, and Oregon), and is the fourth most extensive timber type west of the Mississippi River. On these 5¼ million ha, a significant proportion of trees are dead, having been killed by insects. In the Northern Region alone, a 1979 survey reported 540,862 ha (1,336,496 acres) of lodgepole pine severely infested with mountain pine beetle. Canada has a greater acreage of lodgepole pine forest type (20 million ha or 49.5 million acres, comprising 22 percent of the total forest land in western Canada) than the United States. Most of the North American lodgepole resource is of the variety *latifolia*.

In both countries, much of the lodgepole pine resource is in older (60-200 years) virtually stagnated stands in which growth rate is very low and mortality very high. Typically trees are small in diameter. Perhaps half the North American lodgepole pine volume is in trees 150 mm (6 inches) in d.b.h. or smaller; trees harvested for saw logs probably average less than 300 mm (12 inches) in d.b.h.

Silvicultural treatments (thinning or removal and regeneration to managed stands with controlled stocking) are so expensive, and stumpage revenue so little, much of the acreage has received no treatment to accelerate growth and slow mortality.

OBJECTIVES

Present lack of technically and economically viable utilization alternatives precludes profitable harvest of lodgepole pine in large quantities. Thus foresters cannot manage the species to enhance timber growth, watershed values, wildlife habitat, esthetic quality, and recreational opportunities. In 1982 therefore, the Intermountain Forest and Range Experiment Station initiated a program to invent (or adapt) processes that will permit large-scale profitable utilization of lodgepole pine of all diameter classes on all terrain—while preserving or enhancing other resources. Another objective is to publicize the processes so they will be widely utilized, thereby making possible regeneration of forests of increased productivity.

The research program is modestly funded and is scheduled for completion over about a decade.

OBJECTIVES AND SCHEDULE FOR ACCOMPLISHMENT

Research scheduled to fill technological needs culminates in process invention and application. Routes to achieving such invention vary with investigator. One route that has proven successful – and is contemplated here – calls for a stepwise procedure comprised of the following components, listed in sequence of accomplishment.

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PROGRESS TO DATE

The work to date is on schedule. It is also within budget, largely because the Canadian Forestry Service, through Dr. R. W. Kennedy of the University of British Columbia, is collecting the sample trees from the Canadian portion of the lodgepole range (fig. 1).

Literature Search

Canadian efforts have also facilitated our literature search. Supply and Services, Canada, published in 1983 a lodgepole pine bibliography prepared by Reid, Collins and Associates Limited, Vancouver, B.C., in fulfillment of a contract with the Northern Forest Research Centre, Canadian Forestry Service of the Department of the Environment. The bibliography, comprising 1,318 fully indexed references, is a preliminary step toward the revision of L. A. Smithers' *Lodgepole Pine in Alberta* published in 1961. Abstracts are provided for 936 of the references. The period covered is 1970 to 1973, with a few citations that were considered standard references prior to 1970.

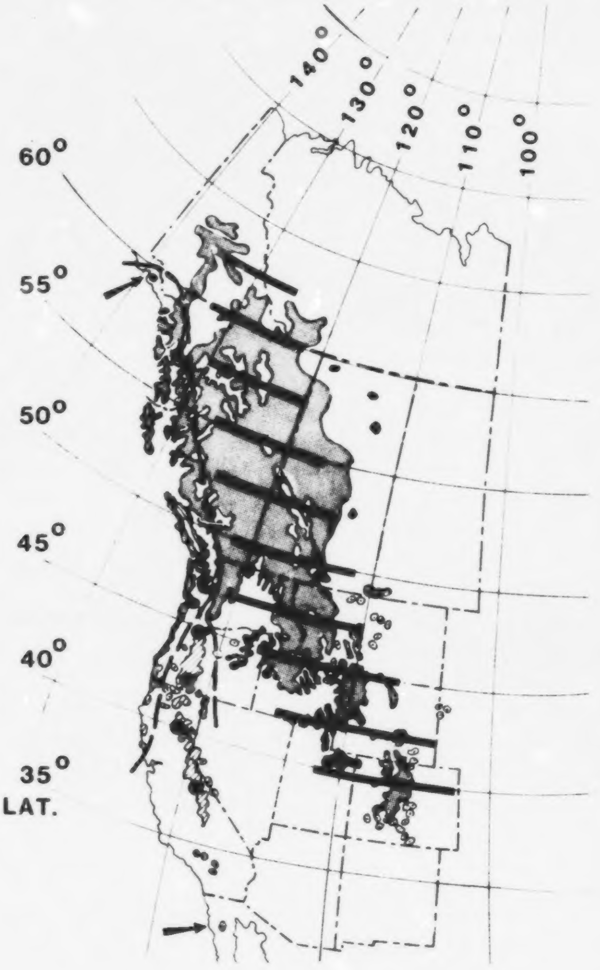

Figure 1. – Sampling zones superimposed on Little's range map of lodgepole pine in North America. Variety *latifolia* is mapped to the right of the dashed lines, *murrayanna* between them, and *contorta* (shore pine) will not be sampled because of its small potential for commercial use. The two arrows indicate outlying populations in north and south.

To date we have accumulated about 2,500 articles related to lodgepole pine and its utilization, 2,000 of which are carded in the new format of the U.S. Department of Agriculture, Forest Service citations. By the end of 1984 we should have nearly 3,000 articles carded. Digestion (analysis) of the articles will begin in 1985, when computer storage will assist in retrieval by subject. The effort will continue for about a decade.

Survey Data

Survey data on the lodgepole pine resource were reported earlier in this symposium. R. C. Kennedy, presented data for Canada; D. Van Hooser, data for the United States.

Uneconomic Stands

During 1983 every State Forester, every Bureau of Land Management (BLM) State Forester, and every National Forest Supervisor within the United States range of lodgepole pine varieties *latifolia* and *murrayanna* was visited (except in California where lodgepole pine is not in excess supply). Each manager was asked to identify within his forest one more-or-less contiguous acreage where increased utilization of lodgepole pine would be desirable, where harvesting could proceed according to a management plan if a commercially viable utilization plan could be invented, and which the responsible forest manager would be willing to market over the next several decades. The areas identified contained not less than 2,000 acres each and might be termed "hopeless cases," where the forest manager could not visualize the stumpage being sold in the near term for conventional processing.

By February 1, 1984, 30 such representative acreages (fig. 2) were identified, totaling about 260,000 ha (641,000 acres), as follows:

State	Cases	Total of representative areas identified in the States	
	(no.)	(M/ha)	(M/acres)
Colorado	5	68	168
Idaho	6	30	75
Montana	6	15	36
Oregon	3	4	10
Utah	1	7	17
Washington	4	89	220
Wyoming	5	47	115
Total	30	260	641

The tabulated areas are only a fraction of the total acreage of economically inoperable lodgepole pine in the United States, but are representative of the problem. In March of 1984, the Nezperce National Forest identified the 2,040 ha (5,040-acre) Kirks Fork area east of Elk City, Idaho, bringing the total number of cases to 31.

Sampling the Lodgepole Pine Population

The primary objective of the collection plan is to obtain three replications of disease- and insect-free specimens of 76-, 152-, and 228-mm (3-, 6-, and 9-inch) lodgepole pine (var. *latifolia*) at low, medium, and high elevations from 10 equally-spaced north latitudes (40 to 62½ degrees) across 10 degrees of longitude, in such a way as to encompass the major range of *latifolia* (fig. 1). A secondary objective is to sample three replications of 3-, 6-, and 9-inch var. *murrayanna* at mid-elevation at four latitudes (37½, 40, 42½, and 45 degrees) in California and Oregon at a single longitude per latitude (fig. 1).

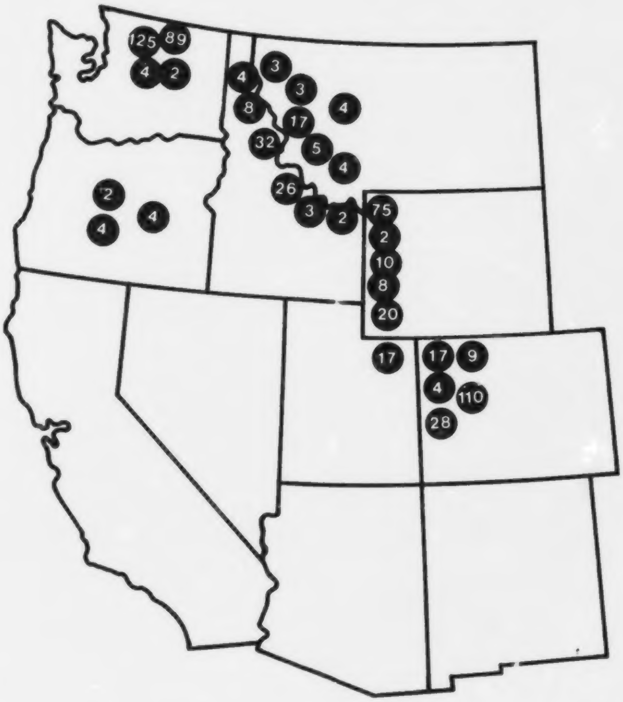

Figure 2.–General locations of 30 representative "hopeless case" acreages of lodgepole pine on public lands. The circled numbers, located by state, indicate thousands of acres.

By the end of 1983, all the *latifolia* sample trees had been collected from latitudes 40, 42½, and 50 degrees, plus six trees from 52½ degrees. Also, half the *murrayanna* trees had been collected, namely, those from 42½ and 45 degrees. The remaining trees of both varieties are scheduled for collection in 1984. Specimens, which include the central stump-root system as well as foliage, cones, branch material, and stem sections, are stored in Missoula.

Characterization of Key Problem Acreages

It is anticipated that the 30 to 35 lodgepole pine stands identified in the United States during 1984 will be mapped, photographed, and inventoried for biomass by the end of 1986. An atlas describing them should be published in 1987. The atlas will include a statement of management objectives for each stand. Because of limited funds biomass will probably be inventoried through aerial photogrammetry supported by limited ground checks. The sampling error, especially in estimating proportions of stand in each size class, may be larger than desired. Precision must be adequate, however, to permit meaningful economic analyses of utilization alternatives.

Characterization of Wood, Bark, Foliage, and Roots

Characterization of tree components as industrial raw material is scheduled to begin in 1985 and should be concluded by 1990. Tree data will be correlated with age and diameter at breast height, elevation, latitude, and perhaps with longitude. Also, within-tree variation in properties with height and radial position will be determined. Scheduled characterization studies will include tree dimensions, moisture content, and weight and also branch size, number, angle, and weight.

Wood and bark of stems and branches will be studied to yield the following data:

Biomass (weight and volume)
Percent compression wood
Spirality of grain
Moisture content
Specific gravity and bulk density
Heartwood ad sapwood volumes
Anatomical dimensions, including proportions of elements, fibril angle, and resin canal frequency
Color
Permeability
Swelling and shrinking characteristics
Chemical analyses, organic and inorganic
Velocity of sound in wood
Heat of combustion and heat of sorption
Fiber saturation point and hysteresis
Friction coefficients
Conductivity, diffusivity, and specific heat
Thermal expansion and contraction
Electrical resistance
Mechanical properties of wood
Mechanical properties of fibers

The wood and bark of the central stumproot mass will be similarly characterized. Cones will be counted and weighed, and their anatomical features and degree of serotiny noted. Data on needles will include weight, moisture content, specific gravity and bulk density, mechanical and chemical analyses, anatomical features, heat of combustion, and adhesive properties.

Process Invention

In my experience, invention of processes peculiarly adaptable to a particular tree species occurs sporadically over a long time span, and then only after continuous immersion in all facets of the subject, i.e., existing literature, the resource, the silvics and physiology of the trees, the character of the tree components (wood, bark, foliage, and roots), and the economic circumstances within the range of the trees.

The needed processes should require moderate amounts of capital, labor, water, and energy. Additionally, they should accommodate trees of all diameter classes, particularly the small diameters, and should yield high-value commodity products – selling for $300 or more per ton f.o.b. mill (ovendry basis) – with a high percentage of wood, bark, roots, and needles converted to salable products.

EXAMPLES OF POTENTIAL PROCESSES

Low-cost harvesting of lodgepole (whether as complete trees with taproot attached, above-ground whole trees, tree-length branch-free stems, random-length logs, stud logs, cordwood, chunks, or chips) is central to successful utilization of the species. Because other speakers at the symposium are addressing this aspect of the problem, I will not dwell further on potential solutions, but simply conclude that solutions must be found for small-stem harvesting on steep and/or unroaded terrain. For the past several years the Intermountain Forest and Range Experiment Station has actively worked to develop new concepts for harvesting small stems on steep and unroaded terrain, and this research will continue through the decade of utilization research herein described.

In the field of processing, two examples illustrate possibilities; the first has progressed through preliminary laboratory evaluation of the concept, while the second is still a matter for conjecture.

Fabricated Joists

Dr. Edwin Burke and I, working at the University of Montana, have demonstrated that very strong and stiff joists can be fabricated with minimally machined whole or half stems of small lodgepole pine as flanges, and ⅜-inch lodgepole plywood or flakeboard as webs (fig. 3).

When tested, the 9½-inch-deep fabricated lodgepole joists with 4-inch half-round flanges and flakeboard webs were stronger in edgewise flexure than the Douglas-fir and larch 2 by 10's and 2 by 12's, and 9½-inch-deep TRUSJOISTS with parallel-laminated-veneer flanges and plywood webs. Moreover, they had significantly less deflection than the 2 by 10's, and joists with laminated-veneer flanges, and were equal in stiffness to 2 by 12's. All of the lodgepole fabricated joists tested (with 2-inch round, and 3- or 4-inch half-round flanges) were significantly stronger and stiffer than the 2 by 10's.

Weights, ovendry, averaged least for the TRUSJOISTS and most for the 2 by 12's, as follows:

Item	Lineal Weight (kg/m)	Lineal Weight (lbs/ft)
Lodgepole joists with 2-inch round flanges		
plywood webs	3.57	2.4
flakeboard webs	4.46	3.0
Lodgepole joists with 3-inch half-round flanges		
plywood webs	3.42	2.3
flakeboard webs	3.72	2.5
Lodgepole joists with 4-inch half-round flanges		
flanges and flakeboard webs	4.46	3.0
TRUSJOINTS	2.53	1.7
2 by 10's	4.02	2.7
2 by 12's	5.21	3.5

It is contemplated that long lengths (perhaps 8½ m or 28 feet to provide clear spans in residences) of one or more styles of lightweight lodgepole joists can successfully compete with 2 by 10's and 2 by 12's, which generally are available only in lengths of 7.3 m (24 feet) or less, and which must be sawn from large logs.

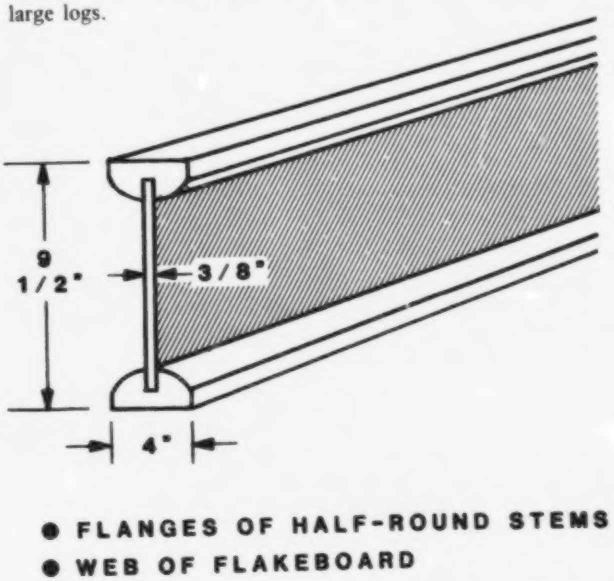

Figure 3.–Lodgepole pine joist. Half-round stems measure 102 mm (4 inches) in diameter inside bark at the small end before edging. In metric terms the joist measures 241 mm deep with web thickness of 10 mm.

Turbine Generator Direct-Fired with Wood

Much timber–particularly in the Intermountain and Rocky Mountain regions of North America–is in unroaded areas where for various reasons an extensive road system is not desirable. Managers of such timber, of which lodgepole pine is a good example, would like to market the trees to finance more intensive management and to reduce losses to insects and disease. Managers need processing plants that can be remotely located in or near the unroaded areas, and that yield high-value products transportable to markets by means other than roads–a system similar to an offshore oil-well platform with pipeline to shoreline refinery. One concept could employ M. Gonsier's long-reach zig-zag cable system to bring wood to the end of a haul road running perhaps 24k m (15 miles) from the center of the entire stand acreage to a nearby plant site accessible year around to workers, and in a location advantageous for connection to a regional power grid. Forest workers would travel to felling sites by fast all-terrain vehicles.

In this concept, a 20-megawatt turbine would be direct-fired with wood previously ovendried by waste heat from the system (fig. 4). The turbine would be connected to a generator and resulting electricity fed into the regional power grid. Were it possible to develop such a wood-fired turbine, overall efficiency should significantly exceed the 25 percent achievable by systems converting wood to steam and then to electricity. Moreover, the direct-fired turbine would use no water–a scarce commodity in many western forested areas.

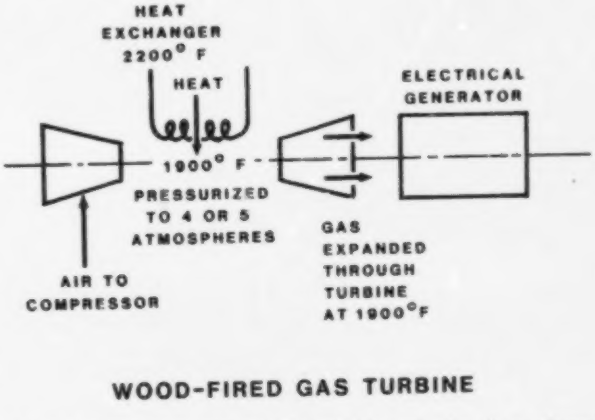

Figure 4.–Turbine-generator set direct-fired with wood, using a heat exchanger to expand compressed air driving the turbine. Heat exchangers operating at 1200°C (2200°F) have not yet been commercially developed. Other configurations that do not require such high temperatures are possible

The turbine, fed with wood, bark, and needles ovendried by exhaust heat, would require about 12 tons per hour; i.e., (20,000 kWh x 3,412 Btu/kWh)/(8,600 Btu/dry pound x 0.33 efficiency) = 24,045 pounds per hour. If the land produced 1 ton of wood (ovendry basis) per acre per year, each hour of operation would remove the annual growth increment from 12 acres. To sustain the operation in perpetuity would require 101,088 acres (12 acres/hour x 24 hours x 351 days/year). If stumpage, harvesting, and truck-haul costs total $35 per ovendry ton, and 1.2 pounds of wood are required to generate 1 kWh, the wood cost per kWh = $0.021. If the power sold at $0.085 per kWh, then $0.064 per kWh is available for profit, depreciation, and operating costs exclusive of wood cost; this amounts to

Table 1.–Potential lodgepole pine commodities ranked according to the gross sales revenue of the product per ton, ovendry, of complete trees required to fabricate the commodity[1]

Commodity	Percent of complete tree[1] used	Gross sales revenue per ovendry ton of the commodity	Gross sales revenue from commodity, per ton, ovendry, of complete tree
	(percent)	(dollars)	
Pulp chips f.o.b. sawmill	60	20	12
Residential firewood, split and loaded on truck f.o.b. woodyard	54 (0.6x0.9)	35	19
Methanol via oxygen-blown gasification and water-shift reaction	60	75[2]	45
2 by 4 studs plus pulp chips	27 (0.6x0.45) 20 (0.6x0.33)	233 for studs 20 for chips	64 (total)
Unbleached kraft linerboard	30 (0.6x0.5)	300	90
Electricity via steam turbine	85	107[3]	91[4]
Structural flakeboard f.o.b. mill	54 (0.6x0.9)	200	108
Electricity via direct-wood-fired turbine	85	141[34]	120[4]
Fabricated truss flanges (fig. 3)	30 (0.6x0.5)	400[5]	120[5]

[1] Biomass percentages of complete trees are approximated as follows (ovendry-weight basis): central stump-root system, 15%; bark-free stem to merchantable top, 60%; stem bark, 10%; branchwood and branchbark, 10%; foilage, 5%.

[2] Plant-gate price of methanol, $0.13/1 ($0.50/gallon); 45 percent yield on ovendry wood, by weight.

[3] Assume gross revenue from electricity at $0.85/kWh with efficiency of 25%, (25% of the heat energy in the wood fed the boiler is converted to electrical energy leaving the generator). Thus 721 g (1.59 pounds) of wood, ovendry basis, are required to generate 1 kWh of electricity.

[4] If efficiency could be raised from 25% for a steam-driven turbine-generator system to 33% for a direct-wood-fired turbine-generator set, this revenue would increase to $120.

[5] Plus some revenue from chips or flakes.

$10,782,720 per year if the plant operates at capacity 50 weeks per year. In metric units, the plant would consume about 10.9 t of wood and bark (ovendry basis) per hour, and would require a land base of 40,909 ha for operation in perpetuity.

EVALUATION OF POTENTIAL PROCESSES

In an effort of this kind, researchers must decide whether their primary clients are tree owners, processing plants, or consumers. I early decided that our purposes were best served, and goals considerably clarified, if the tree owners were considered the primary clients. Having made this decision, one method of evaluating existing or potential processes is in terms of value f.o.b. mill shipping dock of each commodity manufactured by the mill related to the number of dry tons of complete trees (roots, foliage, bark, branches, and stems) required – in the factory, or left behind in the woods – to make the commodity. The idea is illustrated with a simplified example.

Suppose a pulp mill manufactures unbleached kraft linerboard from bark-free stemwood (to a 75 mm top diameter) of lodgepole pine, and that the yield of linerboard is 50 percent of dry weight of dry, bark-free stems entering the mill, and that the bark-free stem to this top diameter represents 60 percent of the ovendry weight of each complete tree. If the linerboard sells for $300 per ovendry ton f.o.b. mill, and the mill sells no other product, this $300 amounts to $300 x 0.6 x 0.5 or $90 per ovendry ton of complete tree on the forest property used to supply the mill.

Results of ranking manufacturing processes by this yardstick are shown in Table 1. Thus pulp chips f.o.b. sawmill have a value *per ton of complete tree, ovendry* of only $12, split residential firewood f.o.b. woodyard $19, methanol f.o.b. manufacturing plant $45, 2 by 4 studs plus pulp chips f.o.b. sawmill $64, unbleached kraft linerboard f.o.b. pulpmill $90, electricity generated by a wood-fired steam turbine $91, structural flakeboard $108, electricity generated by direct-wood-fired turbine-generator $120, and truss flanges fabricated from minimally machined whole stems or half-stems of trees $120.

Obviously, gross revenue data are insufficient to rank investment opportunities; Table 1 is difficult to interpret, but raises interesting questions. For example, if a forestland owner perceived that he could market the annual growth increment of his forest by building and operating one of two plants incorporating proven technology –

> either a kraft linerboard plant using bark-free stemwood only, pulped with a 50-percent yield, with product sold for $300 per ton, ovendry basis,
>
> or a steam-turbine-driven generator plant utilizing all the above-ground tree biomass – but not the roots – and operating it at 25 percent overall efficiency, with his electricity selling to the regional power grid at $0.085 per kWh,

which should he choose? Table 1 indicates that the forestland owner – also the manufacturing plant owner in this case – would receive gross sales from the linerboard plant of $90 per ton of complete tree, or gross sales from the electricity generation plant of $91 per ton of complete tree. Both plants would be very expensive, but possibly a stand-alone generating plant is less complex and expensive than a linerboard plant. Perhaps he would be better advised to make fabricated joists (fig. 3) in a simpler but more labor-intensive plant, for a gross sales return of $120 per ton of complete tree, ovendry basis.

CONCLUSION

The program of research on utilization of lodgepole pine in North America – including characterization data so obtained, and concommitant interest focused on lodgepole – if executed as planned has high probability of stimulating invention of harvesting and conversion processes both profitable and appropriate for improved management of the species.

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THE FUTURE OF LODGEPOLE PINE FORESTRY

THE FUTURE OF LODGEPOLE PINE FORESTRY – A PUBLIC MANAGER'S PERSPECTIVE IN THE USA

Tom Coston

I am pleased to have this opportunity to discuss with you "The Future of Lodgepole Pine Forestry – A Public Manager's Perspective in the USA." First, however, I want to explain why I am pleased. A symposium to accomplish its mission must insure the subject is thoroughly covered. This includes taking a subject that is not noted for being exciting, and through proper lighting and exposure, create a new awareness of its value and importance. And so it is with lodgepole pine and the new lights that have been turned on this species as a result of this symposium. I congratulate the dedication and tenacity of this group for maintaining its enthusiasm about lodgepole pine.

I suspect lodgepole pine had its greatest period of popularity when it was sought by the plains Indians and harvested for lodgepoles. Its light weight compared to its uniform diameter and strength were all good attributes for this purpose. I believe if teepees ever make a comeback, we would have to reconsider our lodgepole pine management objectives.

Now, after attending this symposium and hearing the presentations, I believe we are unravelling the mysteries about how lodgepole pine grows and what its ecological and economic values are.

United States land managers need to know the Rocky Mountains are characterized by large expanses of lodgepole pine. They also need to be aware of the fact these stands present some unique management problems and opportunities, and are the home for valuable wildlife species, especially threatened and endangered species or big game.

The climate in the higher altitudes where most of these stands are located is generally dry, with most of the precipitation occurring as snowfall. Because of this, lodgepole pine watersheds become critical for water users in the valleys below, and they are frequently in areas noted for their overall scenic beauty.

Since man has controlled fires, many lodgepole pine stands have become overmature. In the last 30 years, many thousands of acres have been destroyed by insects or disease. Many are beyond salvage and pose a special threat for disastrous fires.

Lodgepole pine do not attain sizes comparable to other competitive softwoods. Its growth rate, reflective of the poorer sites on which it will grow, which also may include higher logging costs, is frequently below the economic limits prudent managers will consider for sustained yield operations, or even salvage. It is on the lower end of the product value scale for dimensional lumber.

Most important, since lodgepole pine had almost no demand for forest products until after World War II, only about half of the extensive lodgepole pine forests have road access. For many reasons, some managers feel the pressure to keep most of these areas unroaded to protect other values such as wildlife.

The roadless question is perhaps the issue generating the most heat at the present time. Until we know a little more about which lodgepole pine stands will be added to the National Wilderness System and what special considerations will limit standard harvests in other critical areas, we will not be able to provide very reliable figures on the available supply for timber harvest. Special considerations include what and how to harvest in critical grizzly bear habitat, insuring we maintain esthetics in special scenic or recreational areas, or being certain we do not overharvest in critical watersheds. Once these limitations are known, we will be able to predict what will be harvested where, when, and most important, what constraints to development will be necessary. I look for this information to be included in our National Forest management plans which are currently under development. It is also possible legislation will answer the questions concerning wilderness additions.

Because of its smaller size, lodgepole pine in today's economy often appraises as deficit sales. So we will need improved and expanded markets if we expect to sell and harvest much of this material. The most promising new markets appear to be reconstituted products such as flakeboard and waferboard. Technological improvements in harvesting systems are also showing promise for reducing costs. Some of these are new faller-bunchers, prebunchers, miniyarders, grapple skidders, and forwarders.

Management of lodgepole pine is also very important if we are going to manage the insects and disease that create waves of red or skeleton trees. Timely harvesting is the best control we know today to check most of the insects and diseases that decimate this species.

In summary, the mission of today's manager of lodgepole pine is to first determine what stands should be managed for what purposes, then plan for how this will be done and when.

Lodgepole pine, looked down upon by the lumber industry for many years, is finally attaining a respectable place in the lineup of forest resources. Because of its abundance, about 15 percent of the total softwoods in this country is lodgepole pine. Technology and research will improve the value and utility of this species in the years to come. Most important, lodgepole pine forests will continue to serve as an important wildlife home. This forest type, along with a clear rushing stream and a mountain meadow, always has been and always will be symbolic of the Rocky Mountain West. And good managers are always careful about how they treat symbols.

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THE FUTURE OF LODGEPOLE PINE FORESTRY – A PRIVATE MANAGER'S PERSPECTIVE IN THE USA

James E. Bentley

ABSTRACT

Because of the increased number of stud mills built in the 1960s, industrial forest managers began to see more opportunities to convert mature lodgepole pine stands to new stands.

Lodgepole pine forestry exhibits some comparative advantages across the entire spectrum of its management to include seed production, regeneration, growth, and end use.

Lodgepole pine can be labeled a "utility" species since it can be grown comparatively well in many management situations, and used as a raw material for almost all forest products in the northern Rockies.

Industrial land managers will increasingly realize and apply the many attributes of lodgepole pine forestry.

INTRODUCTION

In the 1950s, lodgepole pine from industrial lands in the northern Rockies was used primarily for posts, poles, and railroad ties. During the 1960s, more companies became interested in lodgepole pine and built several stud mills. With the increased use, forest managers began to see more opportunities to convert the mature lodgepole pine stands to new stands (Berntsen, 1973). This paper will discuss some of what Champion's Rocky Mountain Operation in western Montana has experienced in these old-growth conversions, as well as what we anticipate, relating to lodgepole pine forestry and its end-use.

SEED PRODUCTION

An important attribute of lodgepole pine, from a forest management standpoint, is its seed production ability. It is estimated that at 10 years of age, lodgepole pine will be able to produce significant amounts of seed in a seedling seed orchard. This amounts to about five years longer than in a grafted seed orchard. The short time period is a significant advantage compared to ponderosa pine and western larch which begins producing comparable amounts of seed at about 15 years of age. Even in a grafted seed orchard situation, ponderosa pine and western larch seed production is estimated to take up to 10 years. I would expect at least the same excellent seed production under these managed lodgepole pine orchard conditions as compared to natural conditions. With more artificial regeneration activities taking place and contemplated in the northern Rockies, this seed production property could become a valuable asset when managers choose the most optimum species for our future forests.

Lodgepole pine is found associated with two-thirds of the 70 recognized habitat types of Idaho, Montana, and eastern Washington. Douglas-fir, occurring in three-fourths of these habitat types, is the only other species with a wider ecologic amplitude. The wide ecologic amplitude of lodgepole pine is a valuable characteristic, allowing it to be grown in many situations. This, in turn, implies large genetic diversity and a good potential for genetic improvement (Wellner, 1973).

It has been our experience in western Montana that lodgepole pine seed crops occur almost every year. In addition, the species has the ability to retain serotinous cones and its viable seed for several years. This seed production strategy adopted by lodgepole pine lowers the risk of natural regeneration when compared to other species in the northern Rockies (Hellum, 1983).

REGENERATION

In relation to artificial regeneration, it has been our experience that ponderosa pine and lodgepole pine are the two easiest species to grow as 2-0 bareroot seedlings. The pine species grow well the first year and generally become our highest quality bareroot seedlings.

When natural regeneration is the desired strategy, many slash disposal methods generally result in adequate lodgepole pine regeneration. These methods include broadcast burning, lopping and scattering, piling and whole tree skidding. When not having to rely on non-serotinous cones for the seed source, the size of clearcut is of no consequence in relation to regeneration success (Lotan, 1973).

GROWTH

In the northern Rockies, lodgepole pine can be found associated with a large variety of sites that vary from shallow rocky soils to clay hardpans and well-drained soils. However, it grows best on northern aspects that exhibit deep rich soils.

Due to lodgepole pine's cold hardiness characteristics, it is generally the best species, in relation to growth, to be used where frost pocket conditions occur.

Lodgepole pine also has the characteristic of good, young, vigorous growth that will continue to be optimized with proper spacing (Bella, 1973).

The relatively short biological maturity of lodgepole pine fits into the economic based rotations strategy that most industrial landowners are following. Rotations ranging from 60 to 80 years fit appropriately with the 80 to 90 year biological maturity of lodgepole pine.

Lodgepole pine has its share of insects and diseases similar to other associated species. The mountain pine beetle and dwarf mistletoe are the two most common enemies in Montana. When proper spacing and regeneration techniques are followed, future managed lodgepole pine stands should not have these problems. Also, in future managed stands, other insects, diseases, and wildlife enemies will continue to cause loss in timber values. However, as long as the stand is kept vigorous, the losses will be minimized (Ives, 1983).

Lodgepole pine, and for that matter, ponderosa pine tend to be less affected by rootrots such as armillaria than many of the other softwood tree species. The only other species that seems to be less affected by armillaria in Montana is western larch (Byler, 1984).

END USE

Champion's Rocky Mountain Operation uses lodgepole pine primarily in our converting facilities for the production of studs and as interplies for plywood. Whitewood studs consisting of true fir, hemlock, and young ponderosa pine, are generally separated out from lodgepole pine for market purposes. Customer preference and problems with knots and warping of the other whitewood species, tend to lower their stud market values (Benson, 1973).

Locally, lodgepole pine chips are used for production of pulp and paper. Douglas-fir and western larch chips exhibit the strongest fibers, but since residuals from sawmills are the dominant and most economical source of Champion's raw material, we buy what we can and do not separate out the various species. At present, our highest priority is to purchase clean chips with less than 2% bark content.

Utilization of sapling size lodgepole pine for pulp chips holds promise for the future. This is due primarily to the species' relatively thin bark and ease of bark removal.

Hogfuel is a growing energy use for fiber. In relation to this, lodgepole pine ranks in the middle range in heat content compared to the other species in western Montana. The species rank on a drywood basis in relation to producing heat as follows: western larch, Douglas-fir, lodgepole pine, ponderosa pine, spruce, and last are the true firs. Because Champion's pulp mill primarily relies on purchasing mill residual material for hogfuel, we do not presently prioritize the various species (McMichael, 1984).

CONCLUSION

Because of the high cost of money, industrial land managers are continuing to put more emphasis on lowering up-front regeneration and management costs. However, even with the decreased capital available, managers are still expected to do a good job of forest management. Many of the advantages of lodgepole pine forestry fit into this strategy. The species produces seed at a very young age and in a dependable manner. Adequate natural regeneration can be relied on with a high degree of certainty in the northern Rockies. Also, the biological, as well as the economic rotation age, seems appropriate for an industrial forest management strategy.

Lodgepole pine seems to be what I will call a "utility" species. It is a "utility" species in the sense that it is appropriate to grow lodgepole pine for many management situations. The species can be grown well on many variable sites that exhibit extremes in site quality, temperature, elevation, and moisture. In addition, lodgepole pine is used, with few exceptions, for all forest products in the northern Rockies whether fiber or solid wood is required as the raw material.

Lodgepole pine will continue to be an important species in the future wood production of western forests in the United States. In addition, I believe that industrial forest land managers will increasingly realize and apply the many attributes of lodgepole pine forestry.

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FUTURE OF LODGEPOLE PINE FORESTRY: A PUBLIC MANAGER'S PERSPECTIVE IN CANADA

Conway A. Dermott

Lodgepole pine (*Pinua contorta* var. *latifolia* Engelm.) is potentially the most important pine species in the foothills and mountain regions of western Canada. The wide ecological adaptability of this two-needle pine permits it to occupy a large area, a wide range of growing sites and all but the most adverse conditions in Alberta, British Columbia and the Yukon and Northwest territories.

Some authors recognize two varieties of *Pinus contorta*. *Pinus contorta* var. *contorta*, shore pine, is a low shrubby tree of the Pacific coast from southern Alaska to northern California, including the west coast of British Columbia (Little 1953). *Pinus contorta* var. *latifolia* Engelm., lodgepole pine, is the taller and larger-diameter inland form of the mountains from the Yukon to Colorado. The differences in the two varieties are largely in habit rather than in botanical characteristics. This paper deals with the lodgepole pine variety which, in Canada, occurs over most of the province of British Columbia, within the Rocky Mountain Eastern Slopes of Alberta from the U.S. border to approximately 59° N latitude, and in the Yukon and Northwest territories (fig. 1).

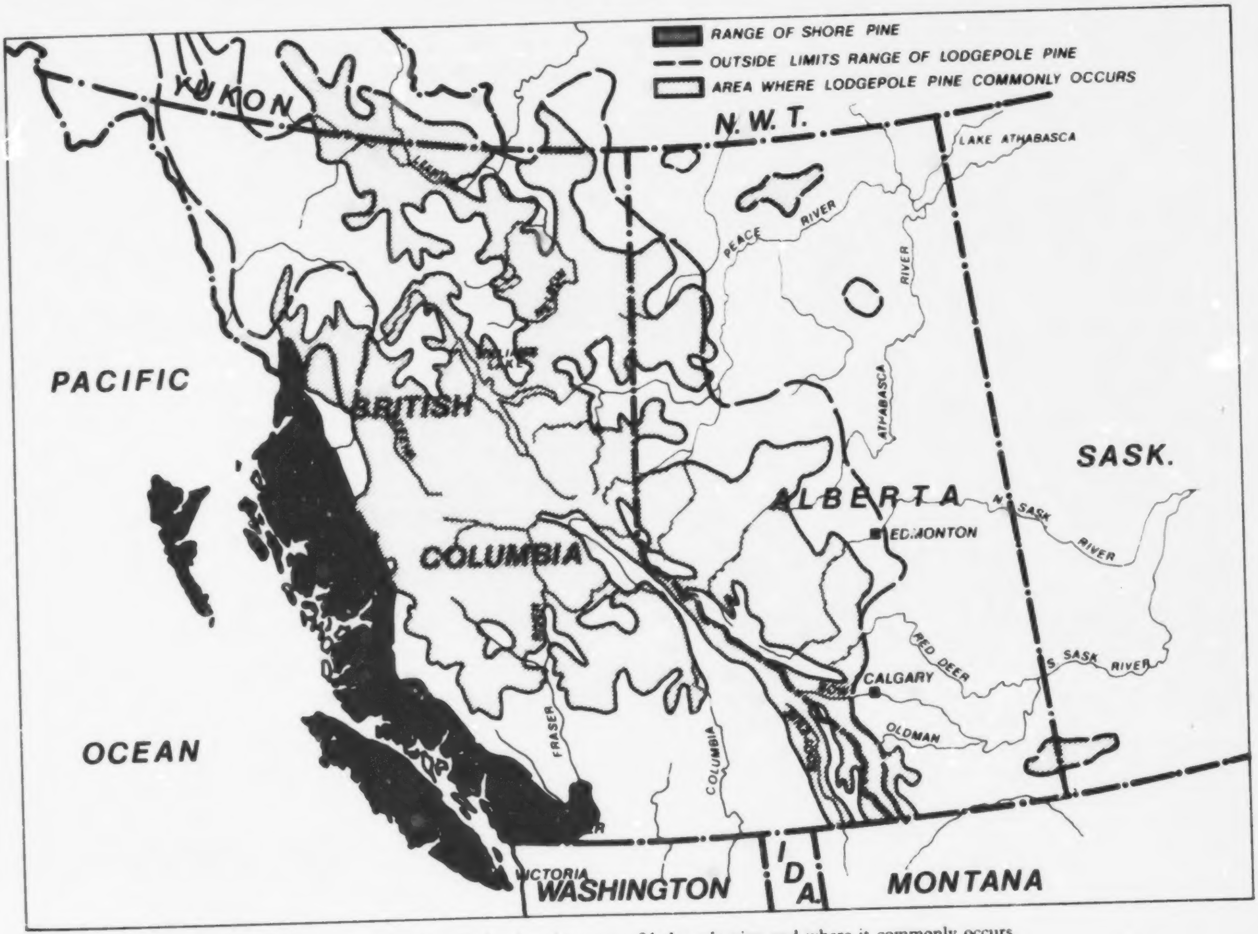
RANGE OF SHORE PINE
OUTSIDE LIMITS RANGE OF LODGEPOLE PINE
AREA WHERE LODGEPOLE PINE COMMONLY OCCURS
YUKON
N.W.T.
LAKE ATHABASCA
PEACE RIVER
RIVER
ATHABASCA
PACIFIC
OCEAN
BRITISH
COLUMBIA
ALBERTA
EDMONTON
SASK.
N. SASK RIVER
RED DEER
CALGARY
S. SASK RIVER
OLDMAN
FRASER
COLUMBIA
VICTORIA
WASHINGTON
IDA.
MONTANA

Figure 1.—Western Canada showing the range of lodgepole pine and where it commonly occurs.

The large area that is occupied by this pine has been, and will continue to be, a major contributor to the softwood timber land base. Lodgepole pine, while only found in the two western Canadian provinces and in the Yukon and Northwest territories, is a major species within the context of the total Canadian forest resource. It occupies approximately 8% of Canada's productive forest land.

Table 1.–Area of lodgepole pine on productive crown forest land in Canada.

Location	Area of Lodgepole Pine Stands[1] (km²)	Area of Forest Stands[2] (km²)	Area of Lodgepole Pine Stands Relative to Area of Forest Stands (%)
Alberta	29,130	198,580	15
B.C.	138,006	450,710	31
Total	167,136	649,290	26

[1] Sources: Alberta data from Alberta Forest Service and British Columbia data from British Columbia Forest Service.

Alberta data excludes forested lands in parks, Indian reserves, Metis colonies and wilderness areas.

British Columbia data excludes forested lands in parks, non-forest reserves and tree farm licences.

[2] Source: Statistics Canada. Canadian Forestry Statistics. 1981.

Note: Lodgepole pine in Canada also occurs in the Yukon and Northwest territories but inventory information is not available.

In the two western provinces, lodgepole pine represents 26% of the productive forest land (table 1). In British Columbia, the area occupied by lodgepole pine forests is very significant to the future forest resource and occurs on 31% of the forest area. In Alberta, the area occupied by lodgepole pine is considerably less than in British Columbia but the species is significant as it represents approximately 37% of the provincial merchantable softwood volume (table 2). British Columbia's lodgepole pine may potentially supply about 16% of softwood volume. No inventory information is available for the Yukon and Northwest territories.

Because lodgepole pine is a major species for the future forest industry in the two western provinces and the territories, and represents a substantial portion of Canada's softwood forest resource, it is considered by many as the second most important coniferous species in the region next to spruce.

FOREST PRODUCTS

Lodgepole pine has provided an opportunity for the forest industry to produce a multitude of forest products. Since the late 1940's and early 1950's, the products produced from lodgepole pine have expanded. It now provides excellent raw material for the pulp and paper industry. The species' color and staining characteristics along with its dimple effect and softness provide excellent qualities for dimension and board lumber manufacturing. It can be readily treated with preservatives and is used widely for posts and poles; recently, large amounts of timbers and lumber have been treated and used in the construction industry. Due to their high pitch content, residues can be used in energy saving products.

The demand for lodgepole pine timber is usually very stable due to the wide range of products that can be manufactured and sold. However, demand for any forest product is relative to the economics of the day. If the forest products market is low, then lodgepole pine products also will be affected.

The production of forest products from lodgepole pine has contributed significantly to the economy of the two western provinces and will contine to do so if the timber resource is properly managed. In Alberta alone, 39% of the manufactured products in 1982 were derived from lodgepole pine. This figure is a significant increase over the 27% and 37% of manufactured production represented by lodgepole pine in 1953 and 1972, respectively. Not only is the species being used in new forest industry developments for a wider range of forest products, it is utilized to higher standards than in the past.

As illustrated in table 3, lodgepole pine is being utilized for a variety of forest products and constitutes a large portion of Alberta's coniferous forest production. As indicated in tables 1 and 2, lodgepole pine both occupies a substantial portion of western Canada's forest land and represents a significant share of the region's softwood volume.

HARVESTING AND MANUFACTURING

It has been long appreciated that natural lodgepole pine reproduction is associated with fire. Natural stands of lodgepole pine are even-aged and occur in association with other species or in pure stands. For the most part, natural stand reproduction ocurs in pure stands. The size of trees within pine types is usually uniform in height and diameter. Harvesting of lodgepole pine often does not require a complex layout system or a variety of logging equipment because the stands are usually pure and even-aged with uniformly-sized timber. The reproductive and stand development characteristics of lodgepole pine make clearcutting a biologically adapted as well as the most feasible and economical silvicultural system available.

Manufacturing of forest products from lodgepole pine is usually easier due to the uniformity in size and the softness

Table 2.—Merchantable volume of lodgepole pine on productive crown forest land in Canada.

Location	Merchantable Volume of Lodgepole Pine[1] (MM m^3)	Merchantable Volume of All Species[1] (MM m^3)	Merchantable Volume of Lodgepole Pine Relative to Merchantable Volume of All Species (%)	Merchantable Volume of Softwoods[1] (MM m^3)	Merchantable Volume of Lodgepole Pine Relative to Merchantable Volume of Softwoods (%)
Alberta	287	1,455	20	777	37
British Columbia	1,246	8,200	15	7,790	16
TOTAL	1,533	9,655	16	8,567	18

[1] Source: Alberta data from Alberta Forest Service (Phase II Inventory); British Columbia data from British Columbia Forest Service (Forest and Range Resource Analysis Technical Report, March, 1980).

Alberta data excludes forested lands in federal parks, Indian reserves, Metis colonies and wilderness areas. Merchantable volumes are based on utilization standards of a minimum 13 cm stump and a 7 cm top diameter.

British Columbia data includes only lands on which the Crown may regulate timber harvesting and excludes agricultural, grazing, residential, industrial park and recreational lands, roads and right-of-way, environmental and other protection areas, and domestic and industrial watersheds. Merchantable volumes are based on a minimum tree size of 17.5 cm d.b.h. and a 10.2 cm top diameter. Stump height is 30.5 cm.

Note: Lodgepole pine in Canada also occurs in the Yukon and Northwest territories but inventory information is not available.

Table 3.—Total coniferous and lodgepole pine production for 1982 from crown-owned lands in Alberta.

Product	Total Coniferous Product Volume (m^3)	Total Lodgpole Pine Product Volume (m^3)
Lumber	4,122,333	1,442,817
Round Timber	158,063	158,063
Pulp Wood	1,010,501	505,250
Woodchips	853,307	298,657
Fuel Wood	79,068	31,627
Railway Ties	17,996	17,996
Slabs	225	79
Lath	63	25
Total	6,241,556	2,454,514 (39%)

Source: Alberta Forest Service Annual Report, 1983.

Note: Volume for lodgepole pine is estimated because coniferous species are not separated in data source.

of the wood. When comparing lodgepole pine to other species, such as white or Engelmann spruce, log size is usually more uniform and requires less complex manufacturing equipment to produce finished products.

REFORESTATION

To manage any species successfully, prompt regeneration after harvesting is critical. This is particularly important in lodgepole pine. The species normally regenerates abundantly following wildfire or site preparation which takes advantage of an abundant natural seed source. Reforestation on harvested lodgepole pine areas can normally be carried out with little difficulty if the right procedures and timing are used.

The strategy adopted for regeneration of lodgepole pine in Alberta and British Columbia includes scarification and the utilization, to the greatest degree possible, of the abundant seed supply in cone-bearing logging slash.

Site preparation is carried out using anchor chain drags (Ferdinand, 1983). When properly used, drag scarification creates favorable micro-sites for seed germination, exposes mineral soil and mixes the duff with the mineral soil, evenly disperses the cone-bearing slash and removes some of the unwanted competing vegetation which may be present. Advantages of anchor chain drags include their simplicity in use and comparatively inexpensive site preparation cost.

Lodgepole pine commonly, but not universally, produces and retains serotinous cones, thus preserving large quantities of available seeds. Prior to cone opening and seed dispersal, the resin bond in serotinous cones must be melted during the hot summer months. As a result, regeneration is partially dependent upon such factors as cone height above the ground and orientation toward reflected solar heat. Drag scarification creates the conditions requisite to cone-opening through dispersing slash and exposing mineral soil.

The timing of site preparation is dependent on the serotiny of the lodgepole pine cones. Northern areas exhibit less serotiny and, to take advantage of natural regeneration, site preparation must be carried out immediately after logging. In the central and southern parts of the region, where cones generally exhibit more serotiny, the timing of site preparation is more flexible.

Taking advantage of natural regeneration based on the existing seed supply will result in even-aged stands which may initially be over-abundantly stocked. Even under overstocked conditions, lodgepole pine in its early stages will exhibit rapid growth. Overstocking can be dealt with through modifications to site preparation or through juvenile spacing. However, excessive stocking in the early stages of growth should not be perceived as a major problem. High levels of natural mortality occur from insects, disease and rodents. Further, lodgepole pine has the capability for differential growth which will result in dominance being established on many sites. Overstocking should not be allowed to continue beyond a stand age of approximately 10-20 years if the highest merchantable volume is to be obtained and stagnation prevented. Generally, poorer sites are more likely to suffer from stagnation.

If carried out after dominance is present, juvenile spacing will allow possible increases in yield. Spacing should be carried out in a manner which will allow for natural mortality and possible wind throw. Spacing densities should take into consideration future harvesting schedules such as commercial thinnings.

In comparison with other softwood species, the cost of regenerating harvested areas is considerably less for lodgepole pine, with very little chance of regeneration failure. Costs saved in regeneration can be directed toward higher levels of management to result in higher-value products.

INTENSIVE FOREST MANAGEMENT

Lodgepole pine normally grows on less fertile and drier soils as compared to adjacent softwood species. These characteristics of lodgepole pine sites, combined with the high densities of stocking after regeneration and rapid initial growth, make this species very favorable for many intensive silvicultural practices. Fertilization of managed stands should provide increased diameter growth of approximately 10% on low-fertility pine sites. Thinning of overstocked natural stands that originated from fire will provide significant increases in merchantable volume. Thinning and cleaning of managed stands will provide increased merchantable volume and avoid stagnation or reduced growth. Lodgepole pine does very well under crowded conditions, and commercial thinning could provide an optimum of value products and a minimum of 15% increased volume. The increase in volume can be obtained by commercial thinning at the proper ages and by utilizing the trees that would normally be lost through natural mortality if left to rotation age. Improved genetic stock can provide significant increases of approximately 8% from first-cycle, 20% from second-cycle and 30% from third-cycle seed orchards.

Some of the largest genetic gain can be achieved, not through volume increases, but by developing disease-resistant strains and material with better wood qualities. For example, the northern softwoods provide the raw material for some of the highest quality kraft pulp, and tree genetics can further improve wood properties which in turn will produce more end product as compared to wood input.

We should not be complacent when viewing the vast area that lodgepole pine occupies and the large merchantable volume available, but rather take full advantage of existing intensive silvicultural practices to improve our forest growth. This species lends itself to achieving increased yields through higher levels of management.

MULTIPLE USE

The lodgepole pine forest presents a unique challenge to the manager for it is doubtful if any other forest combines so many potential uses. In addition to its use as a wood supply, this forest type plays a significant role in watershed, recreation and wildlife habitat.

Because of its wide adaptability to extreme site conditions, ability to regenerate after fire and extensive occurrences in the Rocky Mountains, lodgepole pine is of prime importance in watershed protection. Most major watersheds within British Columbia, Alberta and the territories are protected by lodgepole pine forests. The protection of watersheds in these areas is of prime importance and the role of the lodgepole forest and its management for conservation cannot be overexaggerated. Proper management includes avoiding large areas of over-dense single-age stands which prevent snow fall from reaching the ground.

Lodgepole pine forests, particularly along the Rocky Mountains, provide excellent opportunities for recreation development. These forests usually have clean understories and are free of excessive grasses and shrubs: conditions which are very acceptable to the general public. Construction of recreation facilities is relatively easy as compared to other forest sties which do not have the clean understory and occupy dry soil types. The nature of the stand will withstand heavy recreation pressure, reducing the cost of redeveloping or relocating facilities. In both British Columbia and Alberta, major national parks are located in areas where the prevalent forest type is lodgepole pine.

Lodgepole pine forests provide shelter and some palatable food for wildlife. In comparison with other forest types, mature lodgepole pine forests do not provide high value forage for wildlife but do provide excellent thermal cover and shelter. Forage and browse production increases drastically on newly harvested and regenerated areas. With proper management, forage and browse production can be increased for a certain time period, resulting in increased wildlife populations. Objectives for increasing timber production and for wildlife management can be integrated through planning timber harvests to supply areas of forage, browse, shelter and thermal cover in an optimal mixture.

Withdrawal of forest land for agriculture is less likely than in other forest types because of the less fertile and dry nature of the soils.

Observations have rated lodgepole pine as having a high potential for reclaiming industrially disturbed sites. It is less sensitive to infertile conditions than other species. These observations may lend credit to lodgepole pine being used as an effective coniferous species for afforestation following severe soil disturbance on low fertility forest lands.

PROTECTION

The future of lodgepole pine forests depends on how well we can protect the stands from insects, disease and fire.

While there are many insects which may destroy or damage lodgepole pine stands, the most destructive is the mountain pine beetle. Outbreaks periodically cover many thousands of acres and, unless timely control measures are taken, 80% to 90% of the stand is killed. Outbreaks of mountain pine beetle seldom develop in lodgepole pine stands under 80-90 years of age.

Several management practices can be suggested to reduce the stand susceptibility to mountain pine beetle outbreaks:

1. Old stands containing larger diameter trees should be given cutting priority.
2. The age of stands should be kept to 80 years or less, depending on the wood product requirements and the operational economics.
3. Partial cutting should be avoided.
4. Stand conversion may be considered, although this solution could present other problems.

What is being done about this destructive enemy? Where epidemics are extensive, salvage of dead or dying trees should be carried out in order to utilize the value wood products, and the salvaged areas should be reforested immediately after harvest to ensure a future timber supply. However, the most recent mountain pine beetle outbreak destroyed more timber than could be feasibly salvaged and minor attempts are being made to reclaim these areas.

In areas adjacent to the epidemic region, such as Alberta, control programs are in place to prevent the spread of mountain pine beetle to further high-value forests. Control programs have not been strongly supported by researchers and experts in the entomology field. However, we cannot sit back while high value stands are in danger of attack. Proper management is definitely the best method of reducing the mountain pine beetle problem, although time is required to place all stands in a less susceptible condition. In the short term, if we are to depend on lodgepole pine as a major softwood component, monitoring and control programs must be in place in all areas and scientists must place a higher priority on developing improved and cheaper control techniques.

Many diseases destroy or damage lodgepole pine with dwarf mistletoe being one of its worst enemies in western Canada. Baranyay (1970) estimated annual losses of more than 270,000m^3 in Alberta alone. Attempts to control the disease by repeated sanitation cutting and pruning were unsuccessful (van Sickle & Weggitz 1978). Opening stands by selective logging appears to accelerate the growth of the parasite on the remaining infected trees and results in an increase in the incidence and size of brooms.

Complete removal of infected trees before reforestation is probably the only practical solution. The size of the cutover area should be relatively large to minimize the amount of reinfection from the residual stand. Baranyay (1970) indicated that mistletoe infection from one parasitized residual in a stand of young trees could spread more than 45 m in 80 years. Clear cutting seems to be the best silviculture system for managing mistletoe.

Although inducive to the regeneration of lodgepole pine, fire is also its worst enemy. Practically all lodgepole pine forest may be traced to fire origin (Horton 1956). The fire hazard in lodgepole pine usually exceeds that in similar stands of other species growing in the same vicinity. Within lodgepole pine types, the forest is susceptible to the rapid development of moderate-to-high fire hazards because of the dry sites the species usually occcupies, its characteristic heavy needle litter, the small amount of herbs and shrubs within its stands and the rapid drying of its surface fuels. The annual variation in fire hazard of lodgepole pine is small under conditions of similar weather. In short, extra care and higher levels of fire protection are required in lodgepole pine as compared to associated species.

The future of lodgepole pine depends to a large degree on its protection from insects, disease and fire. Mountain pine beetle control is necessary and improved control methods must be developed. Fire control is an important consideration in managing the species and, with increasing demands for forest products and multiple land use, will become even more critical.

DEMANDS BY PUBLIC

In the past, forest practices have been carried out with little or no attention paid to public interest or concerns. Recently this has changed drastically where various segments of the public have demonstrated a personal interest in management practices on forest lands, particularly public lands. In the future, if forestry operations are to be accepted, managers must place more emphasis on the suggestions of those whom we call "critics".

Silvicultural methods of timber harvesting, debris management, proper road construction and reclamation and overall clean-up must be given a higher priority. As mentioned earlier, clearcutting is the best silvicultural system for the removal of even-aged lodgepole pine timber. Other alternatives do exist such as seed tree and shelterwood harvesting. However, problems such as insect and disease control and prompt regeneration are associated with these methods. To address some public concerns, these methods should be used on a small scale in appropriate locations. Clearcutting, the proven silviculture system for lodgepole pine harvesting, should not be rejected or altered simply because of public concerns. Rather, its continued demonstrated success should be illustrated.

Many concerns and opinions have been put forth against clearcutting. Before rejecting a proven system or throwing the baby out with the wash water, let's first ask why clearcutting is not acceptable. It may be surprising to many that the silvicultural system itself is not the concern, but rather unsightly amounts of debris on cutovers, inadequate erosion control, poor road layout, unsightly landing clean-up, excessive size of cutblocks and the failure to re-establish new forest are of vital public interest.

It is imperative that the forest industry strive to increase public confidence and trust by repeated demonstration that quality management is actually occurring as a physical accomplishment. Cut layouts must take into consideration size, shape, location and depression and be handled with an understanding that scenic values can be protected. Increased utilization and proper debris management will also help build confidence that the job can be done right. Road construction and reclamation along with overall clean-up must be practised on a continuous basis. Other land uses must be considered and appreciated by all forest managers.

Foresters cannot look at the past as the way of doing their job but rather must look to the future and the way it should be done. Industry can no longer calculate the cost of timber harvesting as the only expense but must expand cost estimates to include meeting public concerns. The future of lodgepole pine looks very good and, if higher levels of management are practised to meet public concerns, it looks even better.

In order to meet this challenge our clearcuts must be smaller in size, more esthetically pleasing and promptly regenerated. Let's not look at the past as our forests are full of bad logging practises, poor clean-up and non-regenerated areas which the public continues to use as illustrations of irresponsible management. Meeting public demands is not an impossible task but a simple one. Let's accept the challenge.

CONCLUSIONS

Lodgepole pine is an important tree species in Canada. It occupies a substantial portion of the area and constitutes a significant amount of the timber volume of forested lands in Alberta and British Colmbia. Its wood properties are excellent and it is used extensively for diverse forest products.

Clearcutting is the ideal silvicultural system for this pine as stands are usually of fire origin, pure in species composition and even-aged. Reforestation which utilizes the abundant seed supply in cone-bearing logging slash and drag scarification is effective and economical. Regeneration after harvesting must be prompt to obtain satisfactory seedling establishment from the plentiful seed in serotinous cones. The proven clearcutting silvicultural system must not be changed simply to address public demands. Rather, forest managers continuously have to demonstrate that the system can be used in a satisfactory manner.

The silvicultural characteristics of lodgepole pine make it an excellent candidate for intensive forest management. Practices such as fertilization and pre-commercial and commercial thinnings may be used to increase timber yields. Genetic improvement can be employed to increase disease resistance and improve wood quality in addition to attaining greater yields.

Management of the species for timber must be integrated with other land uses. The goals of watershed, wildlife and recreational managers have to be addressed in a positive manner. Further, it is imperative to incorporate into practice valid public concerns on management, including clearcut size, erosion, control, site clean-up and re-establishment of forests.

The high demand for the lodgepole pine resource increases the importance of improved forest protection. Research on the monitoring and control of mountain pine beetle is a high priority. Fire protection must increase to minimize the loss of lodgepole pine forest.

Lodgepole pine management will present a challenge to the future forest manager. It is an opportunity which we cannot afford to pass up.

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SYMPOSIUM FIELD TOURS: OBSERVATIONS ON LODGEPOLE PINE FORESTRY IN NORTH AMERICA

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and
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ABSTRACT

This report contains observations from symposium field tours to see genetic variation of lodgepole pine at the Priest River Experimental Forest (PREF) in northern Idaho, lodgepole pine forestry in mixed conifer forests of northeastern Washington, and research and management in the heartland of lodgepole pine, near Hinton, Alberta.

INTRODUCTION

Field tours for the Lodgepole Pine Symposium got off to a good start with two full bus loads of foresters and good weather. The tour visited three sites: the Priest River Experimental Forest in northern Idaho, the Colville National Forest in northeastern Washington, and the operations of St. Regis, Ltd., in west-central Alberta.

The Priest River Experimental Forest is a 6,368-acre tract in the Idaho Panhandle National Forests located about 13 miles northeast of Priest River, Idaho. It was established in 1911 as the first center of organized forest research in the Northern Rocky Mountain Region. Since then, major contributions to knowledge have been achieved there in the fields of forest fire, forest management, forest influences, and forest pathology. The Experimental Forest is controlled and directed by the Intermountain Forest and Range Experiment Station specifically for research purposes. The Priest Lake Ranger District cooperates in administration and protection functions, providing a high level of fire protection, road maintenance, and timber sale administration.

The first stop on this field trip was at a 6-year-old provenance test plantation of lodgepole pine located at the PREF arboretum. The plantation contains 75 sources from southeast British Columbia to central Idaho and from low to high elevation. Jerry Rehfeldt contrasted height growth over elevation with growth over latitude. Differences in growth were three times greater for 3,300 feet elevation—the distance from arboretum to Gisborne Lookout (visible from the arboretum) than for more than 300 miles latitude from southern British Columbia to central Idaho. Jerry emphasized that seed can be transferred much farther for latitude than for elevation and that there may be some dramatic gains by moving planting stock short distances uphill from their seed origin. Studies on frost susceptibility and snow breakage are clarifying practical limits to elevational movement.

Research geneticist Jerry Rehfeldt explaining adaptive variation and seed transfer recommendations for lodgepole pine.

Ray Hoff next listed several pests that have been observed in local tests of lodgepole pine. Three of the pests were discussed in detail: needle cast, western gall rust, and pitch nodule moth. For the first two, notable genetic variability was observed both among provenances and among families within provenances. But for the pitch nodule moth, height of the trees was the overriding element responsible for the observed phenotype variation in infestation. We noted that care should be taken in tree improvement programs to reduce rather than inadvertently increase susceptibility to damaging pests.

Next we looked at 90 families of lodgepole pine that were adjacent to the provenance test. Jerry Rehfeldt presented data on the inheritance, genetic correlations, and genetic gains for several traits. Several families were flagged with colored ribbons to illustrate the results of various selection methods. By selecting the best individuals from the best families, an 8 percent gain is possible for height growth. Unfortunately, several other traits such as crown width, branch length, and lateness of growth are highly correlated with height growth; therefore, selection just for height may lead to an undesirable tree and one that would likely be maladapted because it would grow too long into the fall. Jerry has also shown that with a selection for height, but with a 100 percent restriction for the above correlated traits, the genetic gain is 3 percent. When establishing a seed orchard, the product can be designed to fill many of the needs and desires of the forest manager.

Swedish forester Stig Hagner pleased by the growth and development of a 6-year-old provenance test plantation.

The second stop was at a seedling regeneration experiment established by Russ Graham and Al Harvey. Russ showed us some interesting data on the effect of planting beds of various soil materials: mineral soil, normal soil, and an organic soil. Height growth, root growth, number of mycorrhiza, and the amount of various elements in the seedling tissue for three species (western white pine, Douglas-fir, and western larch) were discussed. Because this is just the first year for this study, the data must be considered as preliminary; but it certainly appears that it will have an impact on how seedling beds will be prepared in the future.

We then went to the Station headquarters for refreshments and a self-guided tour of several genetic experiments. Participants viewed several tests underway at the nursery site, including:

1. Lodgepole pine, central Idaho, 89 sources. To be observed and measured for growth parameters and cold hardiness.
2. Lodgepole pine, eastern Idaho and western Wyoming, 60 sources. To be observed and measured for growth parameters and cold hardiness.
3. Ponderosa pine, eastern Washington, northern Idaho, and western Montana, 130 sources. To be observed and measured for growth parameters and cold hardiness.
4. Douglas-fir, midlands (central Montana and east-central Idaho), 77 sources. To be observed and measured for growth parameters and cold hardiness.
5. Ponderosa pine, central Idaho, 30 sources. To be measured for susceptibility to western gall rust. Two tests: one inoculated in a mist chamber in a greenhouse at Moscow and transplanted to this site (near bed, 70 percent infected). The other was inoculated here in the nursery (5 percent infected).

We completed the tour of PREF with a view of a range-wide provenance test of western white pine and of grand fir, and a quick visit through one of the oldest provenance tests in the United States, ponderosa pine established from 1911 to 1916.

NORTHEASTERN WASHINGTON

The Colville Panorama Land field trip gave us a good look at innovative management of lodgepole pine under rather challenging conditions. During early settlement days, forests of northeastern Washington were often high-graded and largely burned over by wild-fire. Precipitation of 20 to 40 inches annually, variable but generally good soils of glacial till and volcanic ash derivation, and a good mix of forest species resulted in dense forest regrowth. With excessive density, many lodgepole pine stands have not reached desired merchantable diameters and may never do so.

Forests in the lowlands of Spokane and Pend Oreille Counties are mostly small, privately-owned tracts, with a scattering of State and county holdings. Suburbanization is expanding in forests within 30 to 40 miles of Spokane, but the population dwindles rapidly. Tiger, for instance, 65 miles from Spokane, is literally a one-store town. The firewood market is strong

Lanny Quackenbush describing small woodlot operations in lodgepole forests.

near Spokane. State foresters are therefore advising stand improvement thinnings, with the better trees left at 8- to 20-foot spacing, depending on the landowner's esthetic sensitivity. Where access is good, firewood brings about $10/cord on the stump, and we saw stands where this amounted to about $400/acre. Marking, quality control, and general administration costs about one-fourth to one-half of the gross, leaving a healthy return to the landowner.

Foresters thinking it over.

Fire control is taken seriously because the area is fire prone and many homes are scattered throughout the forest. The State operates two fire towers and uses both ground support and air-tankers (they really like their water-scooping PBY) for detection and suppression. State and county taxes cover fire suppression programs, with the forest dwellers appearing to be getting a very good deal. The small chipmill at Usk provides additional opportunities for lodgepole pine thinnings and some employment in a generally economically depressed area. The mill's woods crews earn about $5/hour, and a "gypo" operation was seen delivering a small load of lodgepole in a half-ton pickup. The day's price was about $17 a green ton. No one is getting rich, but forestry is at least getting a start and the good site potential of the area portends a better future.

The mountain range between Tiger and Colville is mostly Colville National Forest and State land. These lands were formerly private, mostly returned to public ownership because of tax delinquencies in the Great Depression. Wildfires ravaged the area in the 1930s, leaving mostly a dense, mixed forest of minimal merchantability. A few mature forest stands of about 300 years can be found, and scattered remnants of larch and western redcedar may run up to 700 years old. Lodgepole management on both the Colville National Forest and State lands is similar. Because scenic values are paramount near the highway, shelterwood cutting with directional felling is being used here to produce a more diverse species mix in the next generation. Clearcutting is used in areas with less esthetic sensitivity. Stumpage prices for lodgepole are quite variable, depending on access, timber size, anticipated markets, and even "wild abandon," as they range from $5 to $450/thousand bd. ft.; $20-$30/thousand sales are common now. Lodgepole thinned at about 40 years of age have shown good release response in the Pend Oreille Lakes area, with 5 to 10 rings/inch growth in the next decade. A computer program developed by state foresters showed that thinning is a profitable course of action at a 7 percent interest rate.

The Colville/Kettle Falls area of Stevens County is a major forestry center, with productive sawmills and even a small plywood plant. We visited Posts and Poles, Inc., which is a productive three-man operation relying on the small lodgepole resource. The company produces 400,000 to 500,000 pieces in a good year, and anticipates about 100,000 in 1984. Roundwood is debarked, air-dried and thermo treated with Penta. The deep sapwood of lodgepole is ideal, offering full penetration of the preservative and thereby allowing the company to provide a 25-year decay-free guarantee. Discussion by participants suggested lodgepole could use and easily sustain many more industries of this type.

Some of the waste bark from the Posts and Poles, Inc. plant along with large amounts of sawmill wastes within about a 100-mile radius are destined for the new wood-fired electric generating plant near Kettle Falls. Washington Water Power Co. provided us with an excellent tour of their facility. It has ingenious sawdust/chip unloading and moving equipment, a boiler with eight screw-type feeders designed for mostly suspended burning, and a steam turbine capable of delivering 42 megawatts into the transmission network. With a delivered price for mill wastes (less than 3-inch particle size, and mostly sawdust and shavings) of about $8/ton, the plant produces

Unloading mill residue for the wood-fired electric generating plant at Kettle Falls.

(including capital amortization) electricity at about 55 to 60 mils/kilowatt hour, which compares well with any contemporary competitor. Unfortunately for lodgepole pine, delivered prices for chipped material would probably have to double or triple to be profitable. Nevertheless, our group left with enhanced hope and confidence that renewable forest resources will provide a sustainable energy flow for future generations. When one hears that the world's oil reserves may last only another 35 to 90 years, advances in wood energy appear certain.

Our final stop was in Ferry County where we visited Canyon Creek Campground of the Colville National Forest. This is a nicely located and desirable recreation site in a lodgepole pine type threatened by mountain pine beetle. Robert Chicken and his associates of the Colville National Forest explained how they used crown and sapwood factors to prescribe a reduction from 180 down to 60 ft^2/acre basal area to bring the stand from a dangerous risk to a safe zone. The thinned campground looks attractive, as does the adjoining half-acre clearcut. Other recent thinnings in the nearby East Portal area are also esthetically pleasing as well as helping to prevent an outbreak by the beetle otherwise sure to drastically lower recreational values. Horses were used to yard logs in this area.

Special thanks are extended to Ken Hires and Lanny Quackenbush of Washington's Department of Natural Resources and to Darrell Even, Colville National Forest, for directing the tour while in northeastern Washington.

WEST-CENTRAL ALBERTA

The Hinton tour was designed to acquaint participants with lodgepole pine management in west-central Alberta. The primary emphases were harvesting and regeneration practices, and young stand management. This tour covered two areas of lodgepole pine forest on the leasehold (public lands with a renewable 20-year lease) of St. Regis, Ltd., with some distinct differences in growing conditions and stand composition. According to the Forest Management Agreement (FMA) with the province of Alberta, the company is obligated to "follow sound forestry practices with a view of achieving and maintaining a perpetual sustained timber yield from the productive forest land."

Large-scale logging activity in the region started 30 years ago, with the establishment of a 450-tons-per-day kraft-pulp mill in Hinton and subsequent opening of the area by the development of the all-weather road system. Before that several small portable mills operated in the area, usually near rivers and existing roads, cutting lumber, railroad ties, and pit props for a small local market. These small mills have now all but disappeared.

The entire FMA lease area lies in the eastern foothills of the Rockies. Elevation ranges from 3,000 to over 5,000 feet. Summers are short and cool; winters are long and cold. The mean annual temperature ranges from 1° to 2°C; precipitation from 20 to 30 inches, about one-third of which is snow. July is the warmest and wettest month. The frost-free period ranges from 50 to 80 days, depending on location (elevation). Most the soils are developed from parent material of cordilleran origin. In some locations varying amounts of organic matter accumulates in forms of duff and peat.

Lodgepole pine stands now being harvested are of fire origin, fairly uniform, and cover large, continuous areas. On dry, low-quality sites, where hot fires created plentiful mineral soil seedbeds, excessive regeneration densities may have resulted in overdense stands and a reduction or complete loss of merchantable yield within the usual 80- to 90-year rotation.

Bill Mattes and Bob Udell, St. Regis, Ltd., were the guides for the first half of the tour. This 45-mile loop north of Hinton traversed new climax stands that originated after the logging of climax stands of white spruce-alpine fir over 300 years old. These decadent, overmature stands are potential habitats for a variety of pests and are stagnant in terms of wood production. Such stands are assigned high priority for removal, to be replaced by vigorous new forests. The area also supports some predominantly lodgepole pine stands that originated from fires in 1816, 1822, and 1870.

Harvesting is done in alternate blocks, generally 50 to 150 acres in size to remove 50 percent of standing timber in the first round. The residual blocks are cut 10 to 15 years later, when regeneration in the former cut blocks reaches 6 feet in height. The cutover area is scarified to reduce fire hazard and prepare a receptive seedbed. Seed may come from adjacent uncut spruce and fir stands, or from cone-bearing slash of pine. The treatment is designed to provide sufficient mineral soil seedbed for the establishment of 500 to 1,000 well-distributed seedlings per acre. Harvesting of contiguous blocks is resulting in large areas of young stands. Every area visited had been rigorously treated to obtain natural or artificial regeneration and nearly always successfully.

Stop 1 was at a vigorous spruce-pine plantation established on a level, wet site in 1974. Site preparation involved treating the cutover in 1973 with an angle blade mounted on a crawler tractor, which piled the thick duff layer in continuous rows to expose mineral soil. This operation had to be done in the early spring while the frost could still support the tractor. Planting stock used was grown in Spencer-Lemaire containers and survival was high. Spruce and pine are currently about equal in height – up to 5 to 6 feet. On the other side of the road, we observed an older (1969) plantation of lodgepole in Ontario tubes, which was thriving on a gentle seepage slope. This is one of the few sites where Ontario tubes proved successful.

Stop 2 was to view regeneration resulting from aerial seeding onto snow with helicopters in the early spring of

1970 at a rate of 16 ounces of white spruce and lodgepole pine seed per acre. The stand was logged and blade-scarified in 1969 to prepare a mineral soil seedbed. Seeding resulted in well-stocked regeneration and provided a viable alternative to planting. At present, only moist, north slopes with difficult (expensive) access for planting crews are seeded and usually at a rate of 12 to 14 ounces of seed per acre (spruce 8 to 10 ounces, pine 3 to 4 ounces).

Fourteen-year-old regeneration at Stop 2. (Photo: R. Strang)

At Stop 3 we looked at natural regeneration of lodgepole pine after harvest. Scarification equipment had exposed sufficient mineral soil and scattered the pine cones after harvesting so they opened and dispersed seed throughout the cutover area. Because this type of treatment immediately follows the harvest, no time is lost in establishing regeneration before grasses, herbs, and competing wood species invade the site.

The equipment in most frequent use for site preparation to obtain natural regeneration is a front blade-mounted triple plow on a crawler tractor of D-9 size. Barrels and chains dragged with a D-7 or D-8 size tractor are used on wet areas and on small cut blocks where the moving cost of a large cat makes the former treatment uneconomical. In contrast, site preparation for planting is mostly by Bracke; a C+H plow is used on areas with severe vegetation competition, and a C+S plow is used for winter treatment of wet areas while frozen.

At Stop 4 the group viewed the company's arboretum and test plantations. This is one of two company arboretums located at 4,500 feet (the other is at 3,600 feet), and represents high elevation sites for testing various provenances of lodgepole pine. Plantations established here in 1978 from each of eight seed zones ranging in elevation from 3,500 to over 5,000 feet show no appreciable differences in growth or other characteristics to date. This supports seed transferability without noticeable drawbacks on the FMA lease.

Also of interest were the various lodgepole and jack pine hybrid plantations established in 1972 from 10-year-old transplants. Seed originated from Whitecourt, Alberta, and Petawawa, Ontario, respectively. The hybrids were produced at the Petawawa Forest Experiment Station. So far, the performance of the hybrids is much poorer than that of the local lodgepole pine, except in branch growth, in which respect they resemble jack pine.

Black spruce cutover winter treated with C+S plow. Lodgepole pine and white spruce planting will follow a year later when the ground is settled. (Photo: R. Strang)

On the morning of the second day, the group headed south of Hinton into the heart of pine country with tour guides Jack Wright, St. Regis, Ltd., and Imre Bella and Bill Ives, Canadian Forestry Service, Edmonton. We traveled through an area that was logged in the last 10 years and has larger cut blocks (150 to 300 acres). We saw some 100-year-old pine stands that when harvested yield 40 or more cunits of wood per acre. But in the same stand, some dense patches contain virtually no merchantable stems. A site preparation treatment with drags used after logging in the early 1970's resulted in considerable overstocking of new stands. St. Regis, Ltd., has an ongoing program of precommercial thinning to reduce stand density to around 800 stems per acre. This effort is concentrated on stands that are adjacent to roads and close to the mill. Some precommercial thinning has also been done in young, overdense, fire-origin stands, but this program was terminated because of excessive cost.

We stopped to view a spacing study reported in the Symposium by Wayne Johnstone. Plots were established in 1963 by the CFS in lodgepole pine regeneration that became established after a large fire 7 years earlier. Five spacings (200, 400, 800, 1,600, and 3,200 stems/acre) were replicated twice on three sites (good, medium, and poor). Twenty years after treatment the most dramatic and consistent response, both in diameter and height growth, occurred on poor sites. Optimum spacing, with an eye to merchantable yield at harvest, is around 800 to 1,000 stems per acre. The influence of spacing in thinned plots on height increment and mean height was relatively small and inconsistent. Height growth was generally best at intermediate spacing. Irregular mortality from various causes emerged as a problem between ages 15 and 25 years.

The last stop of the morning was at another CFS study: early stand dynamics of lodgepole pine. The objective of this study is to determine the causes and the amount of mortality between stand establishment and age 30 years, both in thinned and unthinned stands. Numerous insect, disease, and animal damage problems are prevalent and additional information is prerequisite to intelligent management of lodgepole pine.

Although St. Regis, Ltd., is entitled to planting stock from the AFS, they have opted to grow their own seedlings in a greenhouse built for this purpose in 1980. In turn, the company is reimbursed for their seedlings at AFS seedling production cost. This greenhouse can produce one million container seedlings per crop, and up to three crops per year. Most of the second crop and all of the third, is overwintered in cold frames. The seedlings are grown in 2.5 inch^3 Spencer-Lemaire-Ferdinand containers of 102 plants per tray. These containers are designed with vertical ribs to promote downward root growth. When the roots reach the bottom, air pruning enhances lateral growth, which helps to bind the root ball. The seedlings are grown in the greenhouse for 4 to 8 weeks, depending on the crop, then transferred to cold frames for hardening off. The greenhouse is about 3 feet higher than the cold frame area, facilitating seedling transfer by a gravity-feed roller system. Fertilizers are injected into the watering lines for use both in the greenhouse and in the cold frames.

Nearly 30 people from Alberta, British Columbia, Ontario, the United States, and Sweden participated in what most found to be an informative and interesting field tour. For this, thanks are due to Jack Wright and his staff at St. Regis, Ltd., who helped in organizing and running the tours, and to Bernie Simpson, AFS, for the good meals and lodging.

CONCLUSIONS

Interest in lodgepole pine has grown considerably since our first international symposium in 1973. This can be seen by the makeup of symposium participants. Not only were there more of us, even requiring duplicate sessions across the border, but practicing foresters made up a much larger portion of the attendance. Information from scientists is being used, and ideas and innovations are flowing freely in both directions.

Canada now includes lodgepole pine among its top timber species, accounting for more than 10 percent of its total harvest. Large clearcuts, intensive site preparation by mechanical means, and natural regeneration and planting to bring about quick reforestation are commonplace. Information on optimal spacing levels, genetic improvement, and pest control is being accumulated to increase productivity in second-growth forests.

Lodgepole pine management in the United States varies more than in Canada. In the United States, clearcuts are much smaller, broadcast burning is often used in site preparation, and there is more reliance on natural regeneration. Mountain pine beetle and dwarf mistletoe continue to influence management practices over large areas, but we are now smarter on how to minimize their impacts through silviculture. A significant portion of Rocky Mountain lodgepole pine forests are being saved from harvesting through creation of wilderness, and much of the remaining resource carries at least moderate harvesting constraints to protect environmental and social concerns.

Harvesting technology for small timber, efficient utilization, innovative new products, and development of additional markets seem to be key considerations for the future of lodgepole pine as a timber resource. Strong firewood demands, such as we saw near Spokane, were not predicted a decade ago; nor did we foresee the growing interest in flakeboards. Advanced energy production technology and ideas for high-value products such as fabricated trusses are beginning to flow from creative minds. And 10 years ago we did not have the results of plantings in Sweden; intensive forestry and more progressive economics seem so much more possible after hearing of lodgepole's success from Stig Hagner. Surely those of us with "contortaitis" can look forward to another exciting decade.

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POSTER SESSIONS ABSTRACTS[1]

Compiled by
David W. Breuer and Bart J. van der Kamp[2]

FERTILIZING LODGEPOLE PINE IN BRITISH COLUMBIA – A RESEARCH PROGRAM BY THE MINISTRY OF FORESTS

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In 1980, the B.C. Ministry of Forests began an extensive research program to evaluate increment of lodgepole pine after fertilizing with urea. Experiments are situated in stands 15-30 years old, which contained 4000-30,000 stems/ha before thinning. Nitrogen at rates of 100 and 200 kg/ha is applied in plots spaced to 1100, 1600, or 2100 stems/ha, with three replications of each treatment. Since 1981, 11 installations have been established, and plans eventually require more such trials encompassing a range of environmental conditions. Remeasurements at existing sites will be conducted every three years, beginning in the fall of 1984.

Although data for growth are presently unavailable, some short-term results can be summarized:

1. When nitrogen at 100 kg/ha was added to lodgepole pine in October, the average increase in weight of current needles was 37.5% (range 10.0% to 65.9%) during the following season. The corresponding gain from 200 kg-N/ha was 49.7% (range 22.5% to 113.3%).
2. If plots received 200 kg-N/ha, average production of current foliage was 8.8% greater (range −1% to 29%) compared with trees treated at 100 kg-N/ha. Except for two installations, differences between these rates were statistically nonsignificant, but implications for radial increment are unclear since duration of responses is presently unknown.
3. Supplements of urea may alleviate "thinning shock", which is often observed soon after juvenile spacing.
4. On certain sites, beneficial effects of nitrogen might be limited by deficiencies in other nutrients, moisture stress, and damage from squirrels.

STEMWOOD PRODUCTION OF LODGEPOLE PINE: RELATIONSHIPS TO FOLIAR NITROGEN CONTENT AND SITE

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Preliminary results of a study of tree biomass distribution and production of lodgepole pine stands in relation to foliage biomass, foliar nitrogen content and site conditions are presented. Data were collected in twenty-nine stands, ranging in age from 50 to 130 years located at elevations between 900 m and 1500 m in southeastern British Columbia.

Foliage biomass ranges up to $14\ t\ ha^{-1}$ and net current annual increment ranges up to $7.6\ m^3 ha^{-1} yr^{-1}$ in these stands.

Stemwood increment is linearly related to both foliage biomass and foliar nitrogen content. Age is a significant variable in these regression equations. These linear relationships are not influenced by site conditions. However, sites with xeric soil moisture regimes support lower maximum foliage biomass and have a lower foliar nitrogen content than those with mesic soil moisture regimes. This is correlated with a lower maximum stemwood increment on xeric sites.

Nitrogen productivity (stemwood increment per kilogram of foliar nitrogen) is strongly influenced by stand age and does not show a simple linear relationship to foliage biomass. Nitrogen productivity is also probably influenced by deficiencies of elements other than nitrogen and by differences in the allocation of production between above-and below-ground components in response to site differences. The effects of these growth determinants is currently being investigated.

LODGEPOLE PINE NATURAL REGENERATION BY SEED TREES

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Lodgepole pine (*Pinus contorta*) is a major timber species on the Elk City Ranger District. To accomplish regeneration with minimal cost and some reliability of success, several methods have been used to reach this goal. The District has used the seed tree method of regeneration on steep slopes with success. The following criteria were used to help ensure success.

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[1] Presented in alphabetical order by first author.

[2] Compiled by: David W. Breuer, Extension Associate, Washington State University, Pullman, Washington 99164-6410 and Bart J. van der Kamp, Faculty of Forestry, University of British Columbia, Vancouver, B.C., Canada V6T 1W5

1. Need 10-20 seed trees per acre of lodgepole pine.
2. Dominant or co-dominant trees.
3. 50% of the cones on an individual tree have to be serotinous.
4. Minimum of 20-30 tons of slash needed to ensure adequate temperatures to open cones.

Recent research and the District's experience on lodgepole pine natural regeneration with broadcast burning has shown little success. On seed tree harvest cut areas followed by underburning we have had 800-2500 seedlings per acre. This method will be monitored and refined to ensure its continued success.

WATER STRESS RESPONSE AFTER THINNING *PINUS CONTORTA* STANDS IN MONTANA

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Three 50- to 60-year-old lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) stands were thinned in the fall of 1982 to varying densities, each with an adjacent control. A project was initiated to determine the effects of varying basal area reductions on the water relations of the residual trees in the first year after thinning. Pre-dawn leaf water potential measurements were taken monthly in the summer of 1983 using the pressure chamber technique to determine plant moisture stress in the thinned and unthinned stands. An associated study determined soil moisture depletion at depths between six inches and five feet at one of the study sites.

July precipitation was 240% greater than normal causing increased soil moisture and decreased moisture stress from June measurements. Moisture stress increased, however, from seven bars in July to twelve bars in the control in August. The decreased transpiring surface area and canopy interception in the thinned stands caused 12% by volume more soil moisture in the rooting zone.

The following conclusions have been made:

1. The moisture stress for trees in lodgepole pine stands at three sites in Montana decreased after thinning.
2. The decrease in moisture stress was proportional to the basal area removed with the greatest level of thinning exhibiting the lowest moisture stress.
3. Plant moisture stress developed in late summer to near expected levels even with greater than normal early summer precipitation and soil moisture contents.

Measurements of radial increment and height growth of the sample trees in subsequent years will help determine if the phenomenon of thinning shock is related to moisture stress conditions in recently thinned stands.

CERTIFICATION OF LODGEPOLE PINE SEEDS OF CANADIAN ORIGINS UNDER THE OECD SCHEME

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Lodgepole pine seeds of Canadian origin have been exported in considerable quantities to Europe and Scandinavia for a number of years. The international movement of tree seeds for reforestation requires that species and locations of seed sources be properly identified, and certified. Since 1970, the Canadian Forestry Service has been responsible for certifying all forest tree seeds, collected in Canada, for export under an international control scheme established by the Organization for Economic Cooperation and Development in 1967. The operation of the OECD Scheme, specifically as it has applied to lodgepole pine seeds from British Columbia and the Yukon Territory, is reviewed and illustrated.

1. A total of 7330 kg of certified lodgepole pine seeds have been exported between 1970 and 1983, comprising more than 35% of all species exported.
2. Between 1970-75, lodgepole pine seeds comprised 26% of all species exported. This proportion increased to over 42% during 1976-80, and has decreased to 35% between 1981-83.
3. Between 1970 and 1975 over 82% of the exported certified lodgepole pine seeds were from B.C. sources. Since then emphasis has shifted to Yukon seedlots which accounted for approximately one third of export shipments of this species between 1976 and 1980, and almost 70% between 1981 and 1983.
4. Over 1100 kg were exported each year in 1971, 1978 and 1980, reflecting good crops and high interest in the species from other countries.
5. It is estimated that more than 90% of all the exported lodgepole pine seeds have been destined for Sweden.
6. The value of lodgepole pine seeds on the overseas market, based on 1980 estimates of $600 per kg, average approximately $350,000 per year.

GERMINATION OF COMMERCIALLY-COLLECTED LODGEPOLE PINE SEEDS FROM BRITISH COLUMBIA AND THE YUKON TERRITORY

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Lodgepole pine seeds from 173 commercial collections made between 1976 and 1982 and representing 86 geographic seed sources from British Columbia and Yukon Territory, were tested under internationally standardized testing procedures. Each seedlot was tested twice, once without and once with prechill (stratification) to obtain a measure of dormancy as indicated by final germination percentage and speed of germination. Data were summarized by year of collection, latitude and elevation of the seed source.

1. Prechilling increased final germination in two-thirds (67.0%) of the seedlots tested; increases ranged from less than 1% to a maximum of 23.0%, the average being 5.1%.
2. For the remaining lots, prechilling either had no effect or reduced final germination by an average of 2.5%.
3. All seedlots showed an increase in speed of germination (measured as the number of days required to reach 50% germination, designated as R_{50}) following prechilling. On the average, prechilling reduced R_{50} values between 25% and 35%; that is, if unprechilled seeds germinated 50% in 8 days, prechilled seeds required only 6 days.
4. The greatest reduction in R_{50} following prechilling was 47%, i.e. from 10.4 to 5.5 days in a seedlot from central Yukon (lat. 63°30'N).
5. The fastest germination occurred in a seedlot from northern B.C. (lat. 59°30'N) with an R_{50} of 4.7 days; the slowest, with an R_{50} of 9.9 days occurred in a central B.C. (lat. 56°41'N) lot than has consistently proven to be among the most dormant.
6. Overall seed quality averaged approximately 84% prior to 1980; since 1980, average quality has exceeded 92%, perhaps reflecting improvements in processing techniques.
7. More than half of the seedlots tested were collected north of latitude 60°. Seed quality was consistent, averaging 89% to 92% for all latitudes, except between 60°N and 62°N where it was approximately 85%. By latitude, prechilling increased final germination 3% on the average, except between 62°-64°N (33 lots) where the increase was 7%.
8. The effect of prechilling appeared to decrease with increasing elevation of the seed source above 500 m. For seed sources below 500 m there was no effect. Best quality seeds, which germinated more than 90% when prechilled, were obtained from sources between 500-750 m elevation, but all prechilled seeds germinated 85% or more irrespective of elevation.

ENHANCING SEEDLOT QUALITY IN LODGEPOLE PINE BY FLOATATION SORTING

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Lodgepole pine seeds were soaked in water at room temperature for 24h, drained, and incubated at 15°C under light for 72h. Seeds were then dried at 15, 20 or 25°C for 1, 2, 4, 8, 12 or 24h. Dried seeds were placed in water, stirred briefly to dispel surface tension and allowed to settle for about 1 min. Floating seeds were removed separately from those that had sunk; after draining excess water, germination tests (without prechill) were conducted on the "sinkers" and "floaters". The procedure depends on weak and dead seeds relinquishing their moisture reading when dried, so they float when placed in water. Vigorous seeds do not dry as quickly, and sink in water. Sinkers should have higher germination than unsorted seeds. Since some germinable seeds may float, optimum sorting would occur at the greatest difference in germination between sinkers and floaters. Our observations are summarized for two seedlots.

Seedlot A (central B.C. source):

1. Drying for 2h at 15°C produced optimum separation, viz., 92.5% germination for sinkers and 10% for floaters; sinkers represented 91.5% of the original seed bulk. Before sorting, germination was 85.0%.
2. Maximum germination, 96.5%, in sinkers occurred after drying for 24h at 15°C, but these seeds represented less than 38% of the original bulk.
3. Seeds that were soaked, incubated, but were *not* dried, germinated 78% (7% *less* than unsorted seeds) indicating that the procedure *per se* had an impact on seedlot quality.

Seedlot B (northern B.C.):

4. Drying for 8h at 15°C produced optimum separation, viz. 96.5% germination for sinkers and 9% for floaters; sinkers represented 78% of the original bulk. Before sorting, germination was 77%.
5. Maximum germination, 98%, in sinkers occurred after drying for 8h at 25°C, but these seeds represented only 70% of the original bulk.
6. The sorting procedure *per se* appeared to have no effect on this lot.

For both seedlots, increasing the temperature in any drying period increased the proportion of seeds that floated, but near-optimum separations occurred at several drying temperatures and times.

Increases in seed quality of 7.5% and 19.5% were obtained by this relatively simple procedure. If the technique were to be used on a production level scale, such increases are of considerable significance with regard to sowing rules in container nurseries and the cost of raising seedlings for reforestation. Using British Columbia Ministry of Forests estimates, if 1,000,000 seedlings were to be grown from each of the two seedlots studied here, a combined saving of approximately $4500 might be realized. Such increases in quality also have a considerable impact on the price of lodgepole pine seeds exported to other countries.

PRODUCT RECOVERY—LIVE AND DEAD LODGEPOLE PINE

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Dead lodgepole pine has less value for solid wood products than live lodgepole pine. The relative loss in value is dependent on several factors. Time since death is important, but type of product may be even more of a factor. Deterioration causes loss in value of products through losses in volume of lumber or veneer and through lowering the grade of products.

Sawing lodgepole pine for 1-inch boards showed the greatest loss in value between live and dead trees, with losses in both volume and grade. At a random length dimension mill, there was no significant loss in volume. Loss in value was due to lower grade of lumber from dead trees. Peeling lodgepole pine for structural plywood core there was a significant loss of volume from dead trees, but no change in product grades. At a stud mill minor losses in volume plus a small change in grade resulted in a relatively minor loss in value when compared to other product options. Losses in volume can be partially offset by increased chip volume. Losses due to lower product grades cannot be recovered.

WHY MANAGE LODGEPOLE PINE IN THE INLAND EMPIRE?

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Lodgepole pine has many desirable silvicultural characteristics for survival and good growth on a variety of environments. Establishment is relatively easy either by natural or artificial regeneration methods. Disadvantages of managing lodgepole pine are few and mostly a result of historic prejudice.

PEST MANAGEMENT OF LODGEPOLE PINE STANDS IN BRITISH COLUMBIA

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To achieve optimal yield at the earliest rotation age, forest management must encompass pest problems occurring at various stages in the development of a lodgepole pine stand.

Clearcut logging operations facilitate control of two major lodgepole pine pests: dwarf mistletoe from adjoining stands can be controlled by designing cut blocks along natural or man-made borders; and mountain pine beetle infestations can be prevented by harvesting trees before they reach their most susceptible age (80 years or over) and diameter (24.5 cm or over). Stands already infested with mountain pine beetle should be salvage logged before the next flight period to prevent expansion of infestation.

Following logging, mechanical scarification can be used both to provide a favorable seedbed and to remove dwarf mistletoe infected residuals and advanced regeneration.

In areas with large amounts of logging debris, controlled burning can be used to destroy dwarf mistletoe-infected residuals, and in some cases to prevent the build up of secondary bark beetles such as *Ips pini* (Say).

Regulation of stocking density can be used to prevent or reduce pest damage. Snowshoe hares clip and girdle young saplings in areas where they find adequate cover. Thinning may be beneficial in reducing such damage. Lodgepole pine terminal weevil, *Pissodes terminalis* (Hopping), seems to do less well in close spaced stands. Spacing often must be a compromise between that which promotes rapid tree growth, and that which is necessary to control an important pest problem. Other stem diseases such as western gall rust, *Endocronartium harknessii* (Moore), stalactiform blister rust, *Cronartium coleosporioides* (Arth.), and atropellis canker, *Atropellis piniphila* (Weir), may be reduced by selective removal in the course of juvenile spacing operations.

Careful planning and site-specific prescriptions are necessary to anticipate pest problems and prescribe effective management for the development of individual pine stands.

EFFECT OF SIZE OF CLEARING WITHIN MOUNTAIN MEADOWS ON LODGEPOLE SEED PREDATION AND GRAZING ON LODGEPOLE SEEDLINGS

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Lodgepole recruitment into meadows may be reduced by meadow voles (*Microtus montanus*) which eat seeds and seedlings and possibly shrews (*Sorex vagrans*) which may eat seeds. Natural clearings within the meadows may in turn influence the behavior of these small mammals. To test the hypothesis that the size of the clearing might influence grazing or seed predation, circular patches 2 m, 1 m, 0.35 m, and 0 m in diameter were cleared within meadows. In several experiments seeds and seedlings were placed at the clearing center and grazing or seed predation recorded.

The results indicate:

1. There was reduced seed predation in larger clearings.
2. There was reduced grazing on seedlings in larger clearings.
3. There was no statistical difference in grazing load on 1 year vs. 5 week old seedlings.

Larger cleared areas within meadows may provide safe sites for lodgepole seedlings to become established because of reduced vole and shrew activity. Conversely in non-cleared meadow areas, grazing on seedlings may continue beyond the first year with no preference for seedling age. Thus in meadows where seedlings remain small and suppressed, grazing risk may constitute a significant cause of seedling mortality.

FORCYTE: AN ECOLOGICALLY-BASED FOREST GROWTH SIMULATOR SUITABLE FOR USE IN LODGEPOLE PINE MANAGEMENT

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FORCYTE is an ecologically-based forest management simulator suitable for use in evaluating the long-term yield, economics and energy-efficiency of lodgepole pine management.

The 11th version of the model, which is currently being calibrated for lodgepole pine stands in southeastern B.C., can be used to examine the long-term trends in yield and both economic and energy efficiencies of a wide variety of alternative management strategies. This deterministic ecosystem model permits the user to examine the consequences of "what if" scenarios, including different regeneration strategies, fire, insect attack, rotation length, utilization level, fertilization thinning regimes and stocking levels.

The poster presents an example of how the model might be used (based on FORCYTE-10) and describes the overall structure of FORCYTE-11. The adjacent poster describes the work involved in collecting data with which to calibrate the model for lodgepole pine.

INGRESS AND STOCKING IN LODGEPOLE PINE

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The effect of seedling ingress was investigated for scarified, naturally regenerating lodgepole pine sites to evaluate the impact of this ingress on stocking. We examined 41 cutblocks, representing 8 environmental site categories based on moisture regime and competition density.

On favourable sites (52.6% of sample plots) stocking had reached the 80% level before the 7th year regeneration survey was conducted. Stocking continued to increase but reached a maximum well before ingress ceased.

On poor sites (wet, heavy competition: 16% of sample plots) ingress increased stocking well past the 7 year survey date. However, the overall rate of stocking increase was insignificant and planting would be required to meet stocking standards.

Ingress had a significant effect on stocking levels between the 7 year survey and the 10 year deadline on the marginal sites (31.4% of sample plots).

Thus, seedling ingress may cause increased stocking after the regeneration survey is completed, but this effect is strongly site dependent.

WIND FIRMNESS AND ROOT DEVELOPMENT

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The crown, stem and root properties of lodgepole pine and Scots pine were investigated in relation to wind stability in artificially regenerated stands in Sweden. The experimental material was comprised of young seedlings as well as 50 year old trees.

The weight of the root in relation to the crown and the stem was lower for lodgepole pine than for Scots pine. The difference between the species decreased with age, however.

In relation to the weight of the crown and stem, the turning moment required to break down the tree artificially was lower for lodgepole pine than for Scots pine.

The correlation between the wind speed and the movement of the tree indicated a higher movement of lodgepole pine than of Scots pine. The lodgepole pine stem was, however, more elastic.

The stabilizing properties of roots of containerized seedlings were better developed 5 years after planting on Scots pine than on lodgepole pine.

LODGEPOLE PINE SEED SOURCE IDENTIFICATION BY MINERAL PROFILE ANALYSIS

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Elemental profiles for 20 certified and one unknown sample of lodgepole pine (*Pinus contorta* Dougl.) seeds from western North America (11 from Yukon Territory and 9 from British Columbia) were determined by X-ray energy-dispersive spectrometry. Three different multivariate techniques were performed on the spectral variables of each seedlot. Cluster analysis was used to explore any grouping among the different seedlots and to generate hypotheses about the nature of the clusters. The cluster analysis separated the northern and southern groups from each other and the unknown seedlot was correctly grouped with the nearest source seedlot. Results from the discriminant analysis confirmed the clear separation between the northern and southern groups. The provenance of origin of the unknown seedlot was successfully determined through the use of the derived discriminant function. Principal components analysis was used to generate synthetic composite variables which in turn were used in analyses of variance and correlation analyses. The analysis of variance allowed partitioning the total variation among three different levels, namely, between regions (north and south), among seedlots within regions and within seedlots. Clinal variation was demonstrated between the component scores and both latitude and longitude. The applications of this technique in forest seed certification are discussed.

SHOOT AND NEEDLE GROWTH IN PROVENANCES OF LODGEPOLE PINE

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The influence of shoot and needle growth parameters on height growth of lodgepole pine (*Pinus contorta* var. *latifolia*) was studied in seven provenances from all the major site regions in B.C. plus one Yukon provenance growing within a provenance trial at Prince George, B.C.

Fourth whorl shoot and needle elongation was measured periodically in 1983 among provenances from the Yukon (Y), Northern B.C. (NBC), local (L), central dry (CD), coastal transition (CT), southern wet belt (SW), and southern dry area in Rocky Mountain trench (SD). Shoot extension began in early May and needle emergence in mid-May for all provenances. Shoot growth cessation occurred in late May for northern sources (Y, NBC), early June for CT, L, and SD sources, while the SW and CD sources ceased growth in mid-June. Provenances that ceased growth last and had highest elongation rates produced the greatest shoot extension. Proximal needle growth ceased in late July for Y, NBC, and CD sources, early August for L, CT, and SW sources; the SD source ceased elongation in mid-August. While differences in rates, duration and amounts of shoot and needle extension showed a relationship to latitude of seed origin, there was a strong effect due to other environmental factors of seed source.

The number of dwarf shoots on 4th whorl 1983 shoots differed among provenances and was not correlated with shoot length and height growth. The Y source had more than twice the dwarf shoot density of any other source except NBC. This suggests that northern sources are able to initiate a large number of needles in the warmer southern site, but due to the possible influence of photoperiod, stem unit elongation and needle growth were restricted.

The average percent of polycyclic shoots increased to a maximum at year three then decreased in year four in 4th whorl branches in all provenances. There were large differences between provenances in mean percent of polycyclic shoots in each year of branch growth. Also, the number of polycyclic 1983 shoots varied among provenances in the top four whorls. The average percent of polycyclic shoots per provenance was correlated with tree height and shoot length.

BIOMASS DISTRIBUTION IN YOUNG STANDS OF STAGNANT AND NON-STAGNANT LODGEPOLE PINE

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and

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Stagnating lodgepole pine stands and their poor response to management treatments prompted a study to characterize the growth stagnation phenomenon in physiological terms. Twenty-year-old stands near Williams Lake, B.C. that regenerated naturally following wildfire were examined and some aspects of the biomass component of this study are presented here. A range of even-aged plots were selected to represent the growth of trees over a range of stand densities (no. trees/ha) from open to extremely dense conditions, and included four density classes with mid points approximating 5,000, 20,000, 50,000 and 150,000 stems per ha (sph). Above ground tree biomass was partitioned into foliage, branches, and stem components, with foliage and branches further separated by age and branch whorl. Leaf area was determined from geometric relations and regression on leaf dry weight.

The ratio of live crown length to total tree height decreased in ratio from 0.80 to 0.57 for trees grown in open (5,000 sph) and closed (20,000 sph) stands. A second decrease between 50,000 and 150,000 sph (0.59 to 0.51 respectively) indicates stagnation occurs at stand densities greater than 50,000. Declining height growth with increasing stand density suggests that stagnation may begin at lower stand densities, between 20,000 and 50,000 sph (mean tree height of 4.1 and 3.6 m respectively). Maximum per tree biomass was produced at 5,000 sph (7.0 kg/tree dry weight) and declined with increasing density to a low of 0.25 kg/tree in 150,000 sph stands. Maximum biomass per ha, however, was produced at 50,000 sph (53,000 kg/ha) followed by 20,000 (52,000 kg/ha), 5,000 sph (45,000 kg/ha) and 150,000 sph (27,500 kg/ha). Total leaf area (LA), basal area (BA), and bole surface area (BSA) per tree decline with increasing stand density. In contrast, leaf area index (LAI), basal area and bole surface area per ha increase with stand density between 5,000 and 50,000 sph, and then decline to the observed low in the 150,000 sph stands. Basal area and bole surface area per ha estimates have a similar pattern. The ratio of BSA to LA, however, calculated either per tree or per ha, increases with stand density. These results may be significant in explaining the growth stagnation phenomenon in lodgepole pine.

SAPWOOD—LEAF AREA RELATIONS IN LODGEPOLE PINE IN WESTERN MONTANA

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Twenty-eight lodgepole pine trees were destructively sampled. A regression equation predicting leaf area from sapwood area, dominance class, and canopy height was developed. Seven trees were selected at random from each of four plots of different density levels, ages, and habitat types. Leaf area was predicted from sapwood area in twenty-seven plots using the equations developed in this study. Community leaf area was plotted against stand basal area and stand crown competition factor.

1. A non-linear relationship was found between leaf area and sapwood area. Leaf area per unit of sapwood decreased with increasing sapwood.
2. Dominant trees have significantly more leaf area per unit of sapwood than codominant, intermediate or suppressed trees.
3. Leaf area per unit of sapwood area decreases with increasing sapwood.
4. Community leaf area increases linearly with increasing crown competition factor.

Linear coefficients relating leaf area to sapwood area are similar to coefficients developed for lodgepole pine in other studies. The non-linear form found in this study is detectable because of the much larger sample size and the greater variation in size, site quality, and competitive status of trees sampled.

Community leaf area in lodgepole pine reaches a maximum value at the maximum possible density. This is in contrast to the behavior of community leaf area in response to density reported for Douglas fir. Differences between these species are hypothesized to be due to differences in shade tolerance.

SAPWOOD THICKNESS IN *PINUS CONTORTA* DOUGL. EX LOUD.

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The variation of sapwood thickness was studied in relation to the position in the tree, the ages of the tree, the diameter of the tree, the aspect of the tree, the radial growth rate of the sapwood, and the radial growth rate of the whole tree. This variation was expressed by both linear measurements and growth ring counts. The study was carried out on nineteen lodgepole pine trees collected from the east shore of Vancouver Island.

The width of sapwood ranges from 2 cm to 3 cm for both the north and south aspects, except at the ground level, 0.15 m above ground, where it is 5 cm wide. The number of growth rings in the sapwood ranges from 25 to 50 rings, and decreases from the ground level upward to the tree crown. The width of sapwood, in linear measurements, is consistent at various positions along the tree trunk and is independent of tree age, tree diameter, radial growth rate of the sapwood, and the radial growth rate of the whole tree. However, the number of growth rings in sapwood is strongly correlated with tree age, tree diameter, radial growth rate of the sapwood, and the radial growth rate of the whole tree. No statistical relationship exists between the sapwood width and the number of sapwood rings.

COMPARISON OF FOLIAR MACRONUTRIENTS, NEEDLE WEIGHT AND HEIGHT INCREMENT OF LODGEPOLE PINE IN THE KITIMAT VALLEY

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Stand nutrient status (foliar and soil nutrients) was investigated in juvenile plantations of four coastal tree species, including lodgepole pine (*Pinus contorta* var. *latifolia*). The results presented at the poster session include a comparison of foliar macronutrients, periodic annual height increment, total height, and needle weight of ten-year-old lodgepole pine growing on six different sites (landforms/parent materials) in the Kitimat Valley of the Prince Rupert Forest Region.

When comparing similar sites, nutrient levels of P, K, Ca, and Mg in lodgepole pine foliage are less than detected in Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*) of similar age. Of the four species, lodgepole pine exhibits the least variability when estimating the mean of foliar N, P, K, and Ca. With few exceptions, macronutrient concentrations were similar for lodgepole pine on all sites. Lodgepole pine foliage was found to have low to deficient levels of phosphorus and magnesium, particularly on glacial till and outwash parent materials.

Periodic annual height increments for lodgepole pine were greatest on the alluvial site (53 cm/yr), followed by intermediate increment on the outwash and glacial till materials, and lowest values on the colluvial site (28 cm/yr). Under open, freely growing site conditions (excluding the alluvial site), needle weight increases with periodic annual height increment.

Although not included in this poster session, foliar micronutrient analysis, soil nutrient analysis, and other site specific, environmental data (% slope, depth LFH etc.) will be used to assess the growth performance of these four tree species.

The following photo displays were also included:

LODGEPOLE PINE STANDS IN NORTHEAST WASHINGTON

Ken Hires
State of Washington
Department of Natural Resources
Colville, Washington 99114

and

Lanny Quackenbush
State of Washington
Department of Natural Resources
Olympia, Washington 98501

SMALL HARVESTING EQUIPMENT SUITABLE FOR LODGEPOLE PINE

Lee Northcutt and Richard Hallman
Missoula Equipment Development Center
Forest Service, U.S. Department of Agriculture
Missoula, Montana 59806